

SANDIA REPORT

SAND97-1626 • UC-602

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Printed July 1997

Understanding the Dynamics of Water Availability and Use in China

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Understanding the Dynamics of Water Availability and Use in China

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ABSTRACT

This report presents the preliminary results of an analysis of China's water resources, part of an effort undertaken by the National Intelligence Council Medea scientists to improve the understanding of future food production and consumption in the People's Republic of China. A dynamic water model was developed to simulate the hydrological budgetary processes in five river drainage basins located in northeastern, central, and southern China: the Chang Jiang (Yangtse River), Huanghe (Yellow River), Haihe, Huaihe, and Liaohe. The model was designed to assess the effects of changes in urban, industrial, and agricultural water use requirements on the availability of water in each basin and to develop estimates of the water surpluses and/or deficits in China through the year 2025. The model imposes a sustainable yield constraint, that is, groundwater extraction is not allowed to exceed the sustainable yield; if the available water does not meet the total water use requirements, a deficit results. An agronomic model was also developed to generate projections of the water required to service China's agricultural sector and compare China's projected grain production with projected grain consumption requirements to estimate any grain surplus and/or deficit. In future refinements, the agronomic model will interface directly with the water model to provide for the exchange of information on projected water use requirements and available water. The preliminary results indicate that the Chang Jiang basin will have a substantial surplus of water through 2025 and that the Haihe basin is in an

ongoing deficit situation. While the urban water use requirements are met for the Haihe through the year 2025, a small deficit occurs in the industrial sector at 2020, and a large deficit occurs in the agricultural sector throughout the modeling period. The agricultural water use requirements based on grain production indicate that an agricultural water deficit in the Haihe basin begins before the onset of the modeling period (1980) and steadily worsens through 2025. Agricultural water deficits also occur throughout the modeling period in the Huanghe and begin to occur in 1990 in the Huaihe and in 2010 in the Liaohe. In each case in which water use requirements exceed the sustainable yield, it is assumed that the agricultural water deficit must be met by mining groundwater. This assumption is confirmed by reports that groundwater mining is already under way in the most intensely cultivated and populated areas of northern China.

ACKNOWLEDGMENTS

The analysis of China's water resources was a team effort that required the dedicated commitment of many people. We would first like to thank Jay Stewart of Ogden Energy and Environmental Services and Jim Condon and Ron Berger of the U.S. Department of Energy Defense Intelligence Agency, who were instrumental in selecting and defining the initial water basins. Bob Knowles of the U.S. Corp of Engineers provided helpful insights, as did Vern Schneider of the U.S. Geological Survey. We are also grateful to Jim Nickum, who traveled to China during August and September 1996 to collect, translate, and summarize the data from Chinese government agency publications and maps, and to Eric Webb who was largely responsible for the design of the first version of the China water model.

We would also like to thank Chui Fan Chen Cheng of Sandia National Laboratories, who provided assistance with the province-to-water-basin data transformation, and Doug Rizer of Science Applications International Corporation, who assisted with GIS mapping of the Chinese provinces. The estimated water use coefficient ranges for each of the grains were provided by Joe Ritchie, Professor of Agronomy at Michigan State University, and the return flow percentages were provided by Professor John W. Hernandez of the Department of Civil, Agricultural, and Geological Engineering at New Mexico State University. Frederick W. Crook and W. Hunter Colby of the U.S. Department of Agriculture/Economic Research Service provided China grain production and consumption data, the Country Projection and Policy Analysis (CPPA) Model, and CPPA Model reports. Thanks are also due to Dave Harris of Sandia National Laboratories Information Services Engineering, who provided invaluable technical coordination between the modeling teams, and to Nancy Hetrick of Tech Reps, Inc., who provided technical writing and documentation support. Finally, we would like to thank Chuck Meyers of the Lab-Directed Research and Development Program at Sandia National Laboratories, who provided the essential financial support.

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EXECUTIVE SUMMARY

The purpose of this study is to create a better understanding of the dynamics of water availability and use in China, with particular emphasis on the agricultural end-use sector. This study is part of an effort undertaken by the Medea group of scientists at the request of the National Intelligence Council (NIC) to improve the understanding of future grain production and consumption in the People's Republic of China and to make a preliminary assessment of the impact of potential grain shortfalls in China on the world grain market. The effort was initiated in January 1996 to address the question raised by Lester R. Brown in his book *Who Will Feed China?*:^{*} Will China's economic and population growth, coupled with a declining amount of arable land, drive major increases in the demand for grain imports and result in dramatically increased world food prices in the near future? This report presents the preliminary results on the portion of the project that analyzed China's water resources. The contributors are Sandia National Laboratories, the Defense Intelligence Agency, and Ogden Energy and Environmental Services.

The analysis of China's water resources involved developing a dynamic water model to simulate the hydrological budgetary processes in five river drainage basins in northeastern, central, and southern China: the Chang Jiang (Yangtse River), Huanghe (Yellow River), Haihe, Huaihe, and Liaohe. The model was designed to assess the effects of changes in water use in the three end-use sectors—urban, industrial, and agricultural—on the availability of water in each basin and to develop estimates of the water surpluses and/or deficits in each basin through the year 2025. The data was compiled from several sources including Chinese government agency publications. The model allows for both deterministic and stochastic modeling of precipitation and runoff. In the deterministic setting, average annual precipitation and average annual runoff is used in each time step. In the stochastic setting, a series of correlated random values are generated for annual rainfall and runoff using a normal distribution and the mean and standard deviation of these parameters. An agronomic model was also developed to generate projections of the water required to service China's agricultural sector based on historical and projected grain production and compare China's projected grain production with projected grain consumption requirements to estimate any grain surplus and/or deficit.

The analysis included stochastic modeling of the available water in each basin through the year 2025 and comparison of these results with linear projections of water use in each basin to determine the expected frequency of each basin experiencing a water deficit through the year

^{*} See Brown (1995). The issues raised in Brown's book were originally published as an article by Worldwatch Institute in 1994 under the same title.

2025. The water model imposes a sustainable yield constraint, that is, groundwater extraction is not allowed to exceed the sustainable yield (it was conservatively assumed that the rate at which water was withdrawn would not exceed the recharge rate less natural losses; if the available water does not meet the water use requirements, a deficit results). It was also assumed that the impact of any deficit would be felt first by the agricultural sector, followed by the industrial sector, and then finally, the urban sector, which is assumed to always have first priority. The water deficit was estimated for each basin by generating 100 runs of the simulation model and computing the mean and standard deviation of the water deficit for each year through 2025.

The water available for agriculture through 2025 in the Haihe basin was also deterministically modeled, and the agricultural water use requirements for the Haihe basin were projected on the basis of grain production data provided by the U.S. Department of Agriculture/Economic Research Service and grain water use coefficients. The agricultural water use requirements and water available for agriculture in the Haihe basin were compared to predict the agricultural water deficit. The grain surplus/deficit was not computed for the NIC-Medea preliminary results, and the agricultural water deficit was estimated for the Haihe basin only.

The preliminary results indicate that the Chang Jiang basin will have a substantial surplus of water through 2025 and that the Haihe basin is in an ongoing deficit situation. The other three basins generally fall between these two extremes. The results indicate that the total water requirements for the Haihe basin exceed the combined total of sustainable water available from both surface water and groundwater. While the urban water use requirements are met for the Haihe through the year 2025, a small deficit occurs in the industrial sector at 2020, and a large deficit occurs in the agricultural sector throughout the modeling period. The results of modeling the water use requirements based on grain production indicate that the agricultural water deficit in the Haihe basin begins before the onset of the modeling period and steadily worsens through 2025. Agricultural water deficits also occur throughout the modeling period in the Huanghe and begin to occur in 1990 in the Huaihe and in 2010 in the Liaohe. In each case in which water use requirements exceed the sustainable yield, it is assumed that the agricultural water deficit must be met by mining groundwater. This assumption is confirmed by reports that groundwater mining is already under way in parts of northern China, particularly around the Beijing area.

These results have several implications for China if the country is to continue on its present course of rapid economic growth and expanding population, as follows: 1) Agricultural production may need to move from the north to the water-plentiful provinces in southern China (assuming that there is land available for agriculture); 2) The future availability of water in the northern provinces may depend on the transfer of water from southern China and the Chang Jiang (Yangtze) (cost and feasibility will play a role); and 3) China may need to concentrate on

growing labor-intensive fruits and vegetables while relying on imports to satisfy growing grain requirements.

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ACRONYMS

CIA	Central Intelligence Agency
CPPA	Country Projection and Policy Analysis Model
DIA	Defense Intelligence Agency
ERIM	Environmental Research Institute of Michigan
MMT	million metric tons
NIC	National Intelligence Council
NPIC	National Photographic Interpretation Center
SNL	Sandia National Laboratories
USDA/ERS	U.S. Department of Agriculture/Economic Research Service
USGS	U.S. Geological Survey

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INTRODUCTION

The purpose of this study is to create a better understanding of the dynamics of water availability and use in China, with particular emphasis on the agricultural end-use sector. This study is part of an effort undertaken by the Medea group of scientists at the request of the National Intelligence Council (NIC) to improve the understanding of future grain production and consumption in the People's Republic of China and to make a preliminary assessment of the impact of potential grain shortfalls in China on the world grain market. The effort was initiated in January 1996 to address the question raised by Lester R. Brown in his book *Who Will Feed China?*:¹ Will China's economic and population growth, coupled with a declining amount of arable land, drive major increases in the demand for grain imports and result in dramatically increased world food prices in the near future? The complete effort² is schematically represented in Figure 1. This report presents the preliminary results on the portion of the project that analyzed China's water resources. The contributors are Sandia National Laboratories (SNL), the Defense Intelligence Agency (DIA), and Ogden Energy and Environmental Services.

The background immediately following this introduction summarizes the issues raised by Lester Brown. The approach section describes the logic that was used in the analysis, summarizes the model, and describes the analysis that was performed for NIC-Medea. The section following the approach presents the preliminary results. This is followed by a section that discusses the validity of the model and the data. The report closes with a conclusions section, which provides a summary and recommendations.

¹ See Brown (1995). The issues raised in Brown's book were originally published as an article by Worldwatch Institute in 1994 under the same title.

² The complete effort involved input from the U.S. Department of Agriculture (USDA), the U.S. Geological Survey (USGS), the Environmental Research Institute of Michigan (ERIM), the National Photographic Interpretation Center (NPIC), the Central Intelligence Agency (CIA), Sandia National Laboratories (SNL), and the Defense Intelligence Agency (DIA).

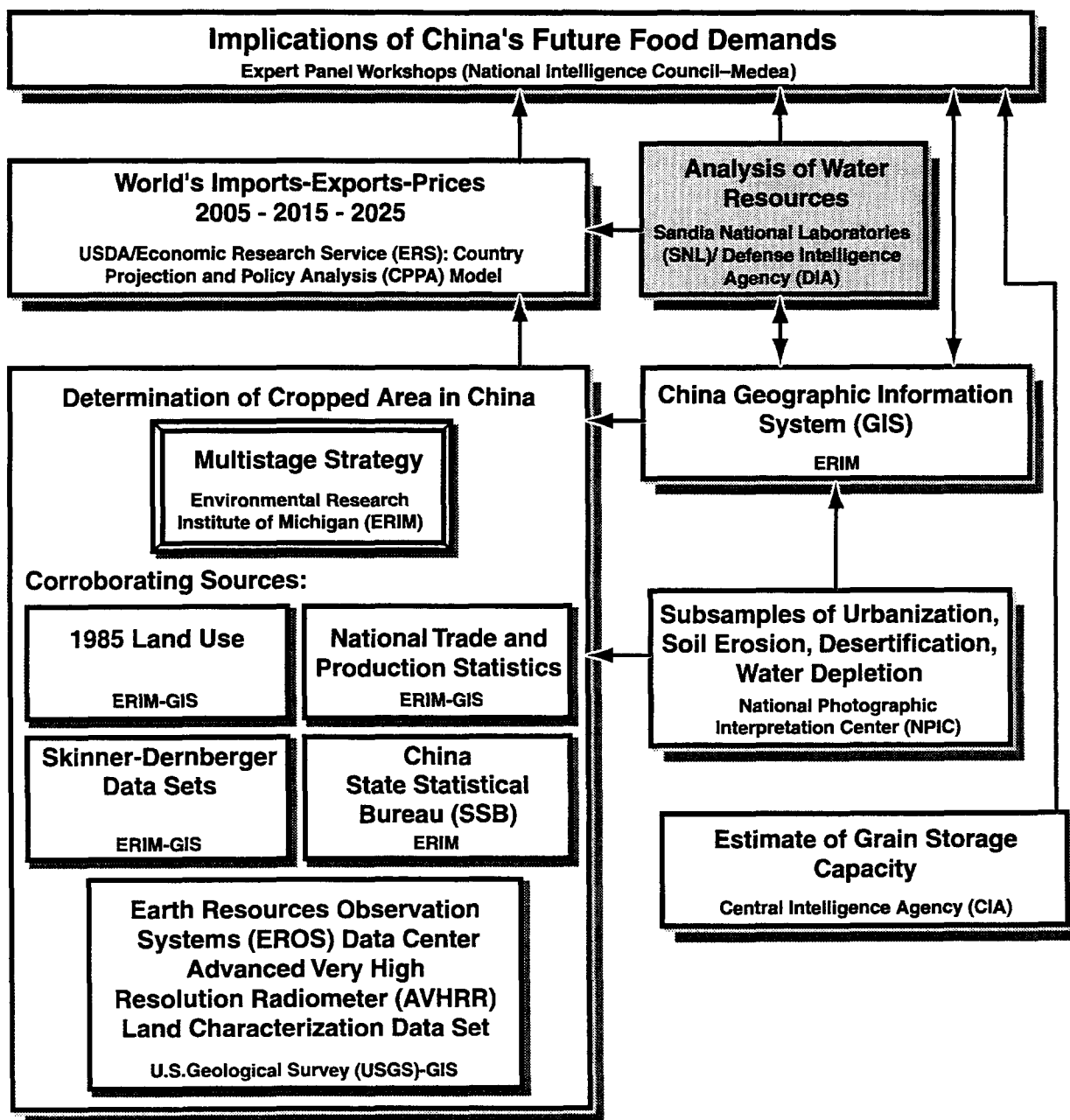


Figure 1. Diagram of NIC-Medea China Project.

BACKGROUND

In *Who Will Feed China?*, Lester R. Brown warns that “China may soon emerge as an importer of massive quantities of grain—quantities so large that they could trigger unprecedented rises in world food prices” (Brown, 1995). Brown compares China with Japan, South Korea, and Taiwan, three countries that were densely populated agronomically when they began to industrialize in the second half of the 20th century. All three countries experienced a conversion of 42% or more of their grainland to other uses and a drop in grain production of at least 24%. By 1994, Japan, South Korea, and Taiwan were collectively importing 71 percent of their grain.

With 0.08 hectare of grainland per person in 1990 (the same as that of Japan in 1950), China is agronomically one of the most densely populated countries in the world. Brown notes that China’s population of 1.2 billion is projected to increase to 1.6 billion by the year 2030. Relying on data from the U.S. Department of Agriculture (USDA), he further notes that roughly one-half of the total cropland area in China is irrigated and that nearly four-fifths of China’s grain harvest is grown on irrigated land. The total area of irrigated land in China nearly tripled between 1950 and the early 1990s. However, in 1977, the irrigated area per person began to decline, dropping by one-fifth by the early nineties. Between 1990 and 1994, grain area in China dropped from 90.8 million hectares to an estimated 85.7 million.

China has also experienced a 56% expansion of its economy since the early ’90s, and income per person has risen by one-half (Brown, 1995). With increasing affluence, China has experienced a dietary shift to greater amounts of animal protein. This translates to an increasing consumption of grain by livestock.

With increased population, industrialization, rising affluence, and the expansion of irrigation, water use in China has increased six-fold since the 1950s. Brown cites the Chinese Minister of Water Resources, Niu Mao Sheng, who stated in late 1993 that more than 300 cities were considered “short of water” and 100 were “very short.” In parts of northern China, agricultural, industrial, and urban water requirements are already being met by pumping aquifers at rates that exceed recharge rates. In much of China, Brown argues, future urban and industrial requirements can be satisfied only by diverting water from irrigation. A heavy diversion of irrigation water to both industrial and residential uses, he states, “is likely to accelerate the long-term decline in grain production now in prospect for China.”

Estimating the potential water deficits in China’s future requires understanding the dynamics of the available water and the expected use requirements. This analysis is an attempt to

dynamically simulate the budgetary processes in China's river basins in order to quantify the role of water in future grain production in China.

APPROACH

A dynamic water model was developed to simulate the available water resources and expected water use in five major river drainage basins in order to develop estimates of the water surpluses and/or deficits in China through the year 2025. An agronomic model³ was also developed to generate projections of the water required to service China's agricultural sector, generate projections of each basin's contribution to China's total grain production, and compare China's projected grain production with projected grain consumption requirements to estimate the grain surplus and/or deficit.

Figure 2 provides an overview of the logic that was used in the analysis. As shown in Figure 2, precipitation, and, more specifically, runoff, are primary drivers in the analysis for quantifying the amount of available water over time (both surface water and groundwater). Water use projections through 2025 are generated using population growth as a basis for the industrial and urban end-use sectors and historical grain production⁴ as the basis for the agricultural sector. As also shown in Figure 2, the analysis accounts for return flow (recycled water) from each of the three sectors back to the water supply. Note that the water model imposes sustainable yield constraints, that is, groundwater extraction is not allowed to exceed the sustainable yield; if the production does not meet the water use requirements, a deficit results.⁵ The projected total water requirements are compared with projections of available water to estimate any water surplus and/or deficit and to determine the expected frequency of water deficits. Population-driven all-China grain consumption requirements can also be computed and compared with projected domestic grain production to estimate any grain surplus and/or deficit.

The locations of the five basins analyzed for NIC-Medea are shown in Figure 3. The five basins, the Chang Jiang (Yangtse River), Huanghe (Yellow River), Haihe, Huaihe, and Liaohe, contain a total of nearly 73% of the arable land⁶ and represent 43%⁷ of the country's mean annual

³ In future refinements of the China water model, the agronomic model will interface directly with the water model to provide for the exchange of information on projected water use requirements and available water. For purposes of the preliminary results, the output from the modeling of available water was entered manually into the agronomic model.

⁴ For the NIC-Medea preliminary results, the grain production data was provided by the USDA/Economic Research Service Country Projection and Policy Analysis (CPPA) Model.

⁵ Under the sustainable yield constraint, groundwater extraction is not allowed to exceed an amount equal to the average recharge plus agricultural return flows. This constraint was imposed because estimates for groundwater reserves were not available. (See Appendix A for further discussion of the sustainable yield constraint.)

⁶ Calculated from data in the ERIM GIS China Land Use Database (ERIM Earth Sciences Group, 1997).

⁷ *Water Resources Assessment for China* (Department of Hydrology, Ministry of Water Resources, 1992).

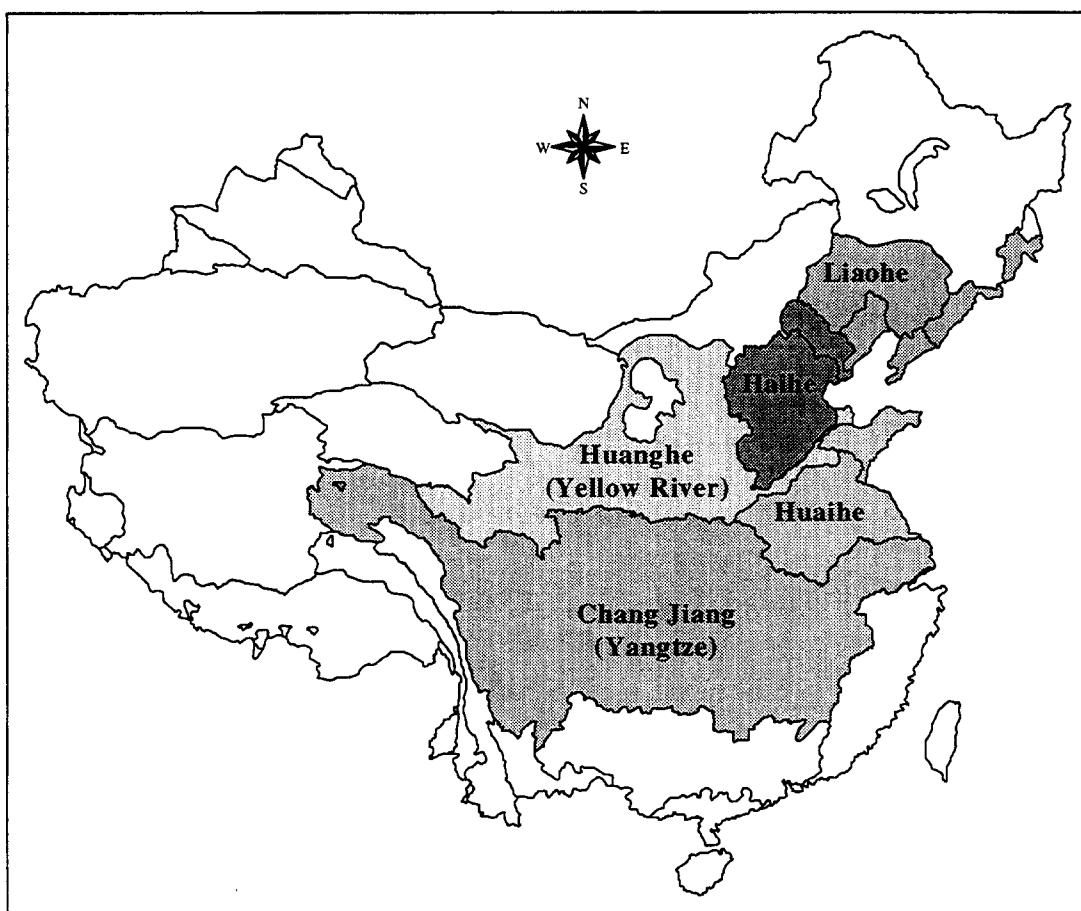


Figure 3. The five water drainage basins studied.

The water model and the agronomic model are summarized below. These summaries are followed by a description of the analysis that was performed for NIC-Medea. See Appendices A and B for detailed descriptions of the models and the data elements used in the analysis.

The Water Model

The water model has two main simulation components: 1) a model of the hydrologic system that quantifies the amount of extractable water available within each water basin and 2) a model of the water use requirements. The hydrologic component simulates the main elements of the hydrologic cycle—precipitation, surface water, and groundwater—in each basin and the movement of water to and from these components, via runoff, groundwater recharge, groundwater discharge, evapotranspiration, and discharge to the ocean, as well as the transfer of water from one basin to another by way of canal (interbasin transfers). The water use component projects the extraction of water from both surface water and groundwater and its allocation between the three sectors, urban, industrial, and agricultural. A water use priority scheme is

imposed as follows: Urban sector requirements are met first, industrial requirements are met second, and agricultural requirements receive the lowest priority. The model allows for both deterministic and stochastic modeling of precipitation and runoff. In the deterministic setting, average annual precipitation and average annual runoff is used in each time step. In the stochastic setting, a series of correlated random values are generated for annual rainfall and runoff using a normal distribution and the mean and standard deviation of these parameters. Projections of total available water and total water use requirements as well as water use requirements for each end-use sector for each basin can be compared to estimate any water surplus or deficit and determine the expected frequency of each basin experiencing a water deficit.

The Agronomic Model

The agronomic model computes 1) a population-driven all-China projected grain consumption requirement by weight for each grain type for each year of the projection on the basis of historical grain and meat consumption patterns and 2) the water volume necessary to produce the grain to meet those requirements using historical grain production data and grain water use coefficients for each grain type (in cubic meters of water per kilogram of grain). The all-China historical grain production is converted to individual basin production to assess each basin's ability to meet those grain consumption requirements with the available land and water resources. The projected agricultural water requirements can be compared with the projected water available for agriculture in each basin to predict the agricultural water surplus or deficit. The total grain consumption requirements can also be compared with projected grain production to estimate any grain surplus and/or deficit.

NIC-Medea Analysis

The following major steps were taken in the analysis of China's water resources for NIC-Medea:

- 1) Collection of baseline hydrological and water use data;
- 2) Development of a parametric computer model of a generic water drainage basin to simulate the hydrological budgetary processes in the drainage basins of major Chinese rivers; and
- 3) Application of the model to dynamically simulate the available water resources and expected water use in the urban, industrial, and agricultural sectors in five water basins through the year 2025.

For purposes of the preliminary results presented in this report, the analysis included 1) stochastic modeling of the total available water in each basin through the year 2025 using an array of data representing the five basins⁸ and 2) comparison of these results with linear projections of total water use in each basin for the period from 1980 to 2025 to determine the expected frequency of each basin experiencing a water deficit through the year 2025. The water deficit was estimated for each basin by generating 100 runs of the simulation model and computing the mean and standard deviation of the water deficit for each year through 2025.

The agronomic model was used to project the Haihe basin's agricultural water use requirements on the basis of grain production data provided by the USDA/Economic Research Service (ERS) and calibrated grain water use coefficients.⁹ The USDA/ERS input consisted of regional historical grain production data from 1980 to 1996 (Crook and Colby, 1996) and regional grain production projections to 2010 generated by the USDA/ERS Country Projection and Policy Analysis (CPPA) Model (*Medea Project (2/10/97): LOTUS Spreadsheet*). The resulting regional grain production data were converted to water basin grain production data. Using the calibrated grain water use coefficients, the agricultural water requirements from 1980 to 2010 were calculated for the Haihe basin. The resulting projection was extrapolated to 2025. These results were then compared with the results of a deterministic run of the water model for the agricultural sector in the Haihe basin to predict the agricultural water deficit for that basin through 2025. The results were also compared with a linear projection of agricultural water requirements based on data from the China Ministry of Water Resources for the Haihe basin consisting of agricultural water use for 1980 and projected agricultural water use for 2020 (see Tables A-6 and A-7 in Appendix A).

Because of time constraints, the grain surplus/deficit was not computed for the NIC-Medea preliminary results, and the agricultural water deficit was estimated on the basis of grain production and water use coefficients for the Haihe basin only. Additionally, for purposes of the preliminary results, uncertainty was not quantified; in future refinements of the model, uncertainty will be quantified using Monte Carlo analysis.

⁸ The data was compiled from several sources including Chinese government agency publications and maps. See Appendix A for a full listing of the sources and for detailed information on the data that was used.

⁹ See Appendix B for descriptions of the computations and calibration.

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RESULTS

The preliminary results of the analysis of China's water resources for NIC-Medea indicate that the water situations in the five basins vary between two extremes: a water deficit throughout the modeling period (the Haihe basin) and a substantial surplus of water throughout the period (Chang Jiang). The Huanghe, Huaihe, and Liaohe generally fall between these two extremes. This section focuses on the results for the Haihe basin and summarizes the results for the Huanghe, Huaihe, Liaohe, and Chang Jiang basins. The Haihe is considered significant because of reports that it has already been experiencing the most serious water shortages (see, e.g., World Resources Institute, 1992; Zhang Qishun and Zhang Xiao, 1995). See also Appendix C for figures illustrating the separate results for the Huanghe, Huaihe, Liaohe, and Chang Jiang basins.

The results of a single run of the simulation model through 2025 for the Haihe Basin showing the available water and the breakdown of surface water and groundwater use are presented in Figure 4. The run generated a series of correlated random values for annual rainfall and runoff using a normal distribution of historic precipitation data. As indicated in Figure 4, the total water requirements for the basin exceed the combined total of sustainable water available from both surface water and groundwater throughout the modeling period. The difference between the total water requirements and the available water is the water deficit, which, it is assumed, is being met

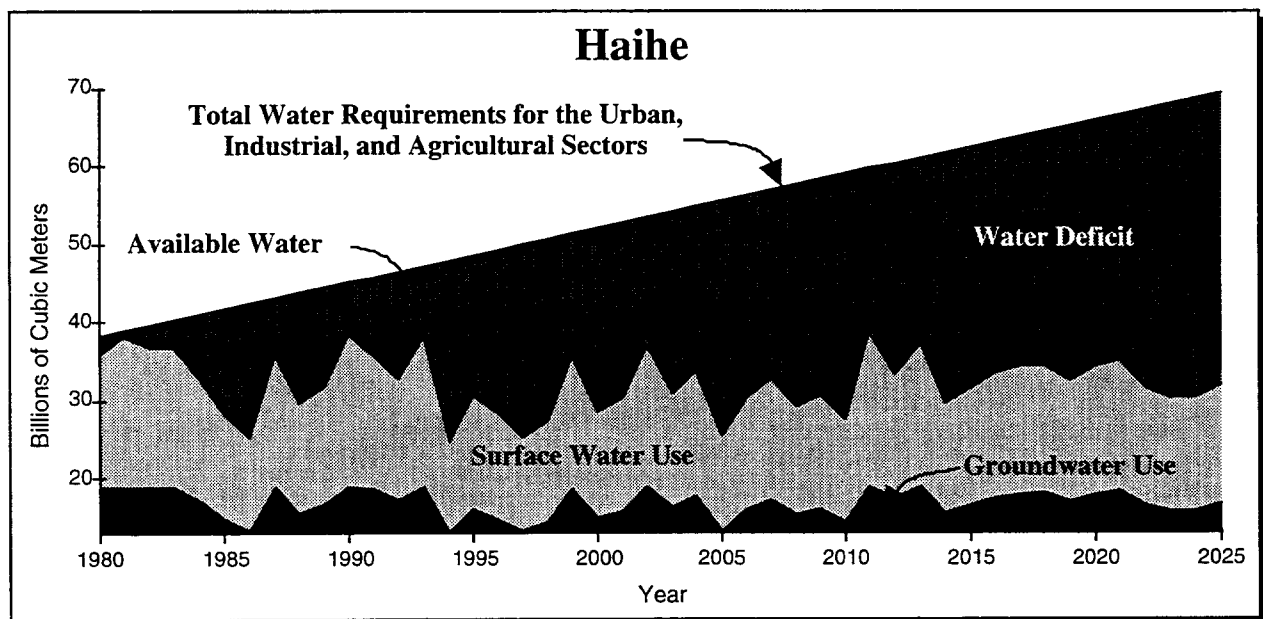


Figure 4. Comparison of the results of a single run of stochastic modeling of available water with linear projection of total water requirements in the Haihe Basin.

by ongoing groundwater mining, a practice that is not sustainable. Although this figure illustrates a single run of the simulation, it is reasonably representative of the predicted water deficit for this basin. See Figures C-2 through C-5 in Appendix C for representative runs for the Huanghe, Huaihe, Liaohe, and Chang Jiang basins, respectively.

Figure 5 illustrates the predicted water deficit for the Haihe Basin through the year 2025 estimated by generating 100 runs of the simulation model and computing the mean and standard deviation of the water deficit for each year through 2025. Calculations based on the assumptions used in the model indicate that there is a probability of 0.68 that the actual water deficit will lie between the upper and lower curves in the figure. For example, by the year 2000, the water deficit in the Haihe Basin is expected to reach 23 billion cubic meters, and the actual deficit is projected to be between 18 and 27 billion cubic meters, with a probability of 0.68. In contrast, the Chang Jiang is expected to experience a water surplus of over 750 billion cubic meters by the year 2000 that will decrease to 650 billion cubic meters by 2025 (see Figures C-7 through C-10 in Appendix C for the predicted water balances for the Huanghe, Huaihe, Liaohe, and Chang Jiang basins, respectively). Table 1 presents a summary of the frequency of each basin experiencing a water deficit through the year 2025 based on 100 runs of the model.

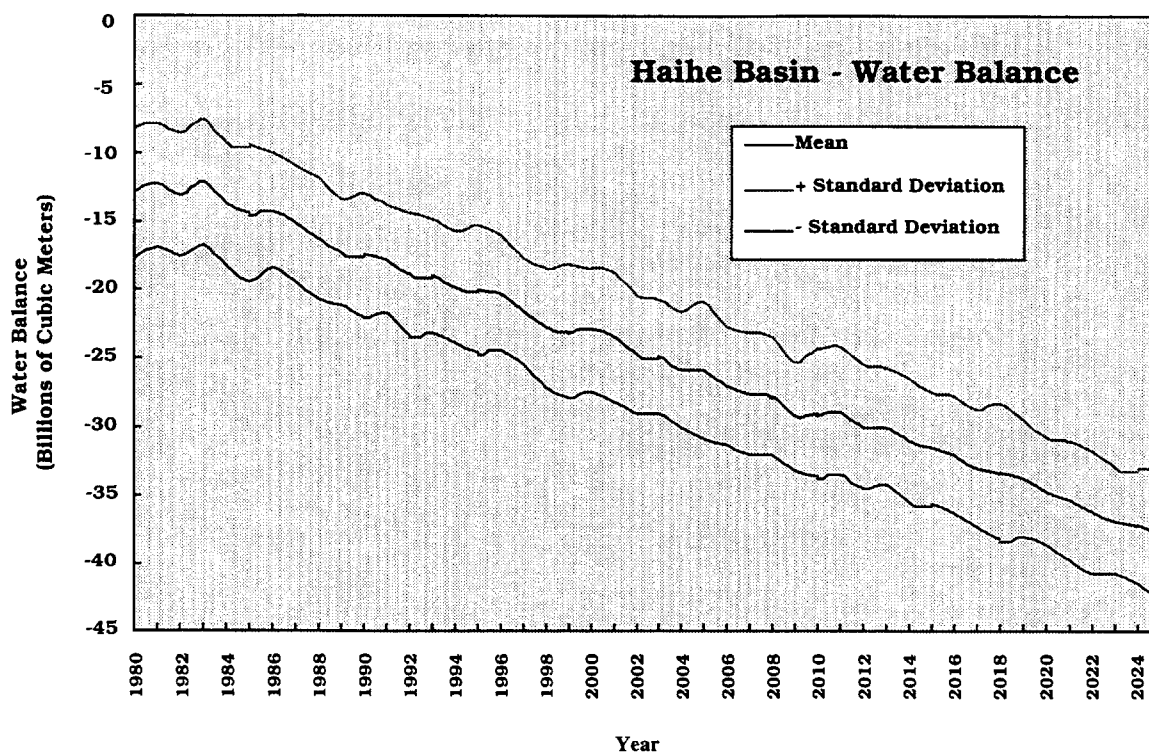


Figure 5. Predicted water deficit for the Haihe Basin through the year 2025 generated in 100 runs of the simulation model.

Table 1. Expected Frequency of Each Basin Experiencing a Water Deficit Through the Year 2025

Basin	Frequency
Haihe	Always
Huanghe	Almost Always
Huaihe	Occasionally
Liaohe	Almost Never
Chang Jiang	Never

Note that the impact of the deficit is felt first by the agricultural sector, followed by the industrial sector, and then, finally, the urban sector, which is assumed in the model to always have first priority. Figure 6 presents the results of a single stochastic run of the simulation model through 2025 for the Haihe Basin and the breakdown of water use by sector. As shown in Figure 6, the urban water requirements for the Haihe basin are met through the year 2025. A small deficit occurs in the industrial sector at 2022, and a large deficit occurs in the agricultural sector throughout the modeling period. The agricultural sector deficit steadily worsens through the year 2025. As shown in the figure, this is due not only to the increasing water requirements for agriculture but also to increasing urban and industrial requirements, which receive priority. In

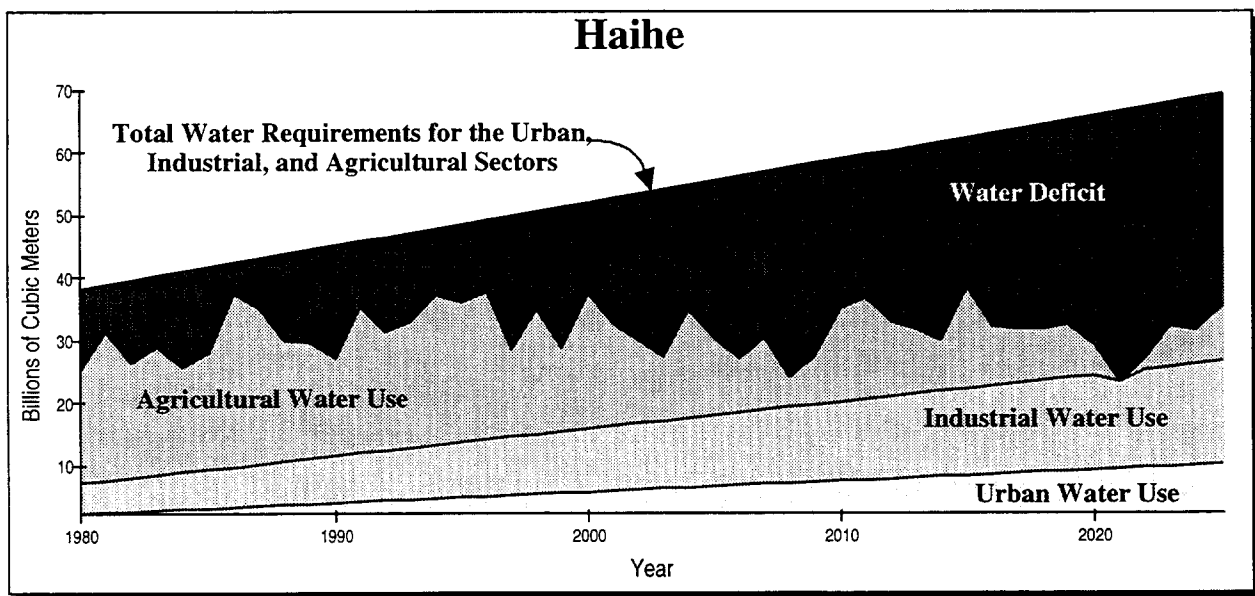


Figure 6. Comparison of the results of a single run of stochastic modeling of total available water and water use in the urban, industrial, and agricultural sectors with linear projection of total water requirements in the Haihe Basin.

the Huanghe, Liaohe, and Huaihe basins, the water requirements in the urban and industrial sectors are met through the year 2025, but water deficits occur in the agricultural sector throughout the modeling period in the Huanghe, and begin to occur in 1990 in the Huaihe and in 2010 in the Liaohe. (Figures C-12 through C-15 in Appendix C show the water use breakdown by sector for the Huanghe, Huaihe, Liaohe, and Chang Jiang basins, respectively).

Figure 7 presents the agricultural water deficit for the Haihe basin from 1980 to 2025. The figure compares the results of deterministic modeling of the projected water available for agriculture in the Haihe basin with 1) agricultural water requirements generated in the agronomic model and 2) a linear projection of agricultural water requirements based on data from the China Ministry of Water Resources. The agricultural water requirements generated in the agronomic model were projected on the basis of grain water use coefficients calibrated for the Haihe basin combined with 1) USDA historical grain production data to 1996 and 2) data for regional grain production to 2010 generated by the USDA/ERS CPPA Model. The resulting projection was then extrapolated to 2025. The data from the China Ministry of Water Resources consisted of agricultural water use for 1980 and projected agricultural water use for the year 2000.

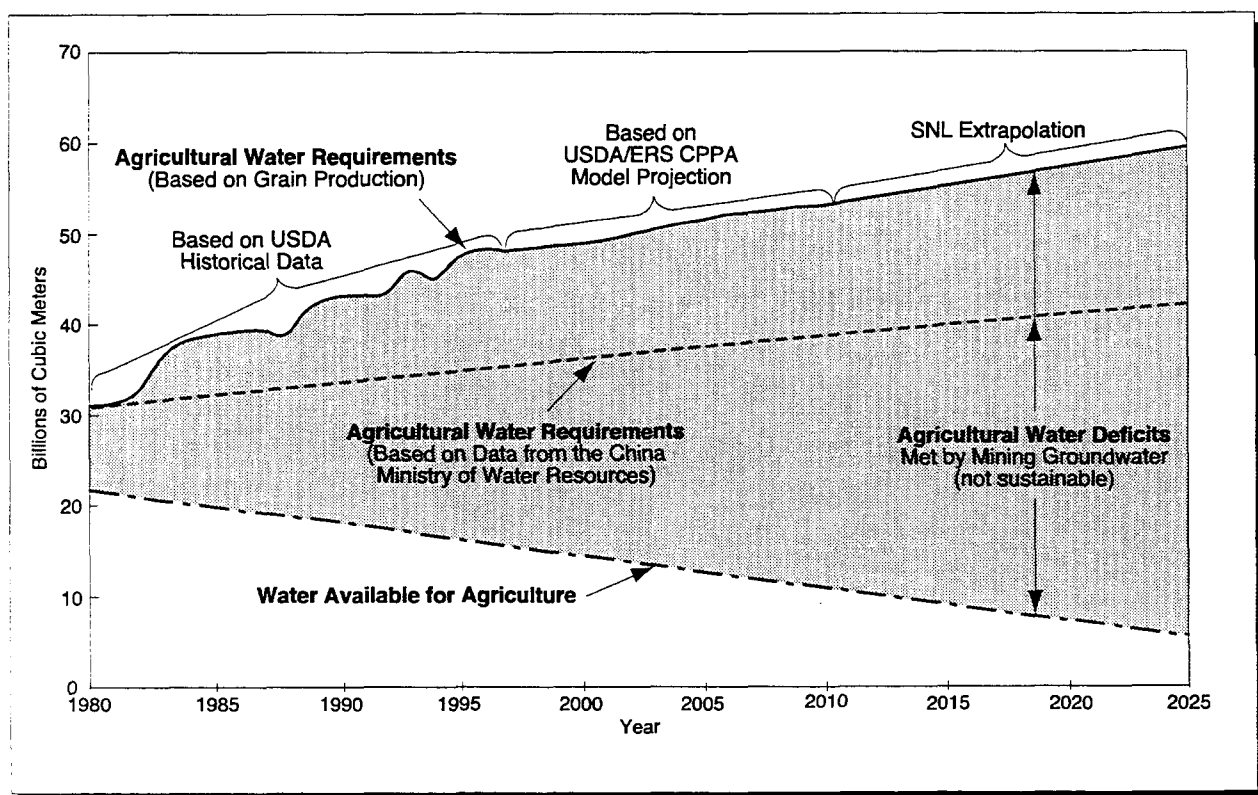


Figure 7. Comparison of projections of agricultural water requirements and water available for agriculture for the Haihe basin through 2025.

In the figure, the agricultural water deficit is presented as the difference between the agricultural water requirements and the water available for agriculture (the sum of available groundwater and available surface water). As indicated above, the impact of any deficit is felt first by the agricultural sector. The wide divergence between the two projections of agricultural water requirements illustrates the uncertainty of the data used to generate them. Both projections, however, indicate an agricultural water deficit in the Haihe basin that begins before the onset of the modeling period and steadily worsens through 2025. As stated above, because the water use requirements exceed the sustainable yield, it is assumed that the deficit is being met by mining groundwater.

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VALIDITY

The purpose of this analysis was to improve the understanding of China's water balance at the river drainage basin level, with an emphasis on the agricultural end-use sector. Specifically, the intent was to estimate the water surplus and/or deficit in five basins. An important question that arises with a projective modeling exercise such as this is "How valid are the results?," that is, "Does the model provide projections that can be relied on to indicate a real problem that needs to be addressed or are the projections artifacts of a faulty or inadequate model?"

Water Model Assumptions

- 1) The stochastically generated time series for precipitation and runoff are perfectly correlated. The model assumes that years with high precipitation correspond with high runoff years. Neither of these time series is autocorrelated; that is, multiyear patterns of drought and flood are not represented. Neither precipitation nor runoff is correlated between basins.
- 2) Annual recharge is calculated to always be proportional to runoff on the basis of the historical recharge/runoff relationship. Surface water reservoir storage is assumed to not hold water from one year to the next, but it is also assumed that within any year there is sufficient reservoir storage to hold water until it is needed within that same year.
- 3) When the water use requirement is greater than the available water, the basin is not operating on a sustainable yield basis and groundwater mining is assumed to be occurring. The water deficit is the difference between the total water requirements and the available water. Time to depletion cannot be determined because the exact amount remaining is unknown.
- 4) When groundwater extraction is less than groundwater recharge and the basin is operating on a sustainable yield basis, excess groundwater is discharged to surface water and excess surface water is discharged to the ocean.
- 5) The proportion of groundwater extraction to surface water extraction is maintained at 1980 levels until groundwater extraction exceeds sustainable yield or surface water extraction exceeds the available surface water.
- 6) Water use requirements for the three sectors are met in the following order of priority: urban receives first priority, industrial receives second priority, and agricultural receives last priority. The agricultural sector returns water to both the groundwater system and the surface water system, whereas the urban and industrial sectors return water only to the surface water

system. Return flows are assumed to be proportional to the water use within each of these sectors.

Water Model Data

The data used in the water model are from several sources, but most of the data were taken from one source, *Water Resources Assessment for China*. This source was originally prepared in Chinese and was translated into English at Hohai University, Nanjing. In the absence of any evidence to the contrary, it was assumed that all data, no matter the source, were derived in a manner that is consistent with the data descriptions provided in *Water Resources Assessment for China*. There were a number of instances, however, where the data descriptions were insufficient. As a result, significant uncertainty remains about whether the water model has been properly parameterized.

For example, the description of evapotranspiration data from *Water Resources Assessment for China* states that runoff is subtracted from precipitation and that the remainder is assumed to have been removed from the system through evapotranspiration. The document, however, does not indicate whether agricultural evapotranspiration, especially that portion of agricultural evapotranspiration from irrigation water, is included as part of the evapotranspiration term or whether it is considered to be a water withdrawal from the surface water and/or groundwater systems.

Additionally, for data that was collected, translated, and summarized from Chinese government agency data tables, it was not possible in all cases to interpret accompanying text that might have explained how the data were derived or their intended use. The data that came from *Water Resources Utilization in China*, in particular the data for water use requirements, fell into this category. In general, it could not be determined whether the water use requirements from *Water Resources Utilization in China* are net requirements (which would not include any return flows) or gross requirements (which would include return flows). It also could not be determined whether the data summarizing the agricultural water use requirements were restricted solely to irrigation water or whether the definition of agricultural water use also includes water consumed in dryland farming.

Agronomic Model Assumptions

- 1) The value used for daily caloric requirements was 2,250 calories per capita, the median of the accepted range for the United States, which is 2,000–2,500 calories per capita per day. This figure will be revised when a better estimate becomes available.
- 2) The all-China projected caloric requirements for each year were apportioned between the three major grains (rice, wheat and corn), meat, and “other” (which included other grains and fruits and vegetables) in accordance with Chinese historical grain and meat consumption patterns from the USDA (USDA/ERS-730).
- 3) To account for the caloric inefficiency of meat production, the caloric requirements value apportioned to meat consumption was converted to grain-equivalent caloric requirements using a grain-to-meat ratio coefficient of 4:1.¹⁰ The assumption was made that, in the aggregate, meat animals consume grains and grain equivalents in the following proportions: rice–15%, wheat–15%, corn–50%, and other–20%.
- 4) Values used for the average caloric content for each grain type and for meat in calories per gram were as follows: rice–3.63, wheat–3.35, corn–3.65, other–3.54, and meat–3.48. These values were obtained from the *USDA Nutrient Database for Standard Reference* (1997).
- 5) The calibrated water coefficients were presumed to be acceptable for all years for which the model was run.
- 6) It was assumed that factors for same-grain multiple-cropping were implicitly captured to the first order in the grain yields obtained from the USDA. Future refinements to the model are planned for computations for multiple-cropping of different grains.

Agronomic Data

Table 2 presents a comparison of the grain and meat requirement values for 1996 that were generated in the agronomic model with 1994-96 grain consumption data from USDA/ERS. As shown in Table 2, the values generated in the model agree favorably with the USDA data.

¹⁰ Meat animals are inefficient producers of calories for human consumption. For example, seven kilograms of grain equivalents are required to produce one kilogram of beef, and two kilograms of grain are required to produce one kilogram of poultry (see *The Economist*, November 16, 1996). The ratio of 4 kilograms of grain equivalents to one kilogram of meat is an intermediate value between the values for beef and poultry. It was used in the model as an aggregate approximation for all meat consumed in China. This value will be disaggregated into individual meats in future refinements of the model.

The projections for agricultural water requirements generated by the model also agree favorably with the agricultural water usage data that were obtained from *Water Resources Utilization in China*, to the extent that the model's grain requirement compares with USDA data on historical grain production. This is to be expected because the water coefficients that were used to generate the agricultural water requirements were calibrated on the basis of historical data from that document as well as historical grain production data from USDA/ERS-730.

Table 2. Comparison of the 1996 Projected Grain and Meat Consumption Requirements Generated in the Agronomic Model with 1994-96 Grain Consumption Data from the USDA/ERS

	Agronomic Model 1996 Values (consumption requirements)	USDA/ERS* 1994-96 Estimates (amount consumed)	Difference (%)
Rice			
Total (MMT) [†]	123.09	128.48	-4.2
Per Capita (kg)	101.31	105.70	-4.2
Wheat			
Total (MMT)	116.70	111.68	+4.5
Per Capita (kg)	96.05	89.30	+7.6
Corn			
Total (MMT)	105.80	105.86	-0.1
Per Capita (kg)	87.08	87.10	--
Other			
Total (MMT)	61.56	N/A	--
Per Capita (kg)	50.67	N/A	--
Meat			
Total (MMT)	42.44	52.50	-19.2
Per Capita (kg)	34.93	43.50	-19.7
* Crook and Colby, 1996			
† MMT = million metric tons			

COMMENTARY

Summary and Conclusions

The analysis of China's water resources presented in this report is part of an effort undertaken by the Medea scientists to improve the understanding of future food production and consumption in the People's Republic of China. A dynamic water model was developed to simulate the hydrological budgetary processes in five river drainage basins in China: the Chang Jiang (Yangtse River), Huanghe (Yellow River), Haihe, Huaihe, and Liaohe. The model was used to assess the effects of changes in urban, industrial, and agricultural water use requirements on the availability of water in each basin and to develop estimates of the water surpluses and/or deficits in China through the year 2025.

An agronomic model was also developed to generate projections of the water required to service China's agricultural sector, generate projections of each basin's contribution to China's total grain production, and compare China's projected grain production with projected grain consumption requirements to estimate the grain surplus and/or deficit. The model was used to project the agricultural water use requirements of the Haihe basin on the basis of USDA/ERS grain production data and calibrated grain water use coefficients.

The preliminary results of the stochastic modeling of China's water resources for the five basins indicate that the water situations in the five basins vary between two extremes: a water deficit throughout the modeling period (the Haihe basin) and a substantial water surplus throughout the period (Chang Jiang). The other three basins generally fall between these two extremes. The results indicate that the total water requirements for the Haihe basin exceed the combined total of sustainable water available from both surface water and groundwater. A water-use breakdown for the Haihe basin indicates that, while the urban water requirements for the Haihe are met through the year 2025, a small deficit occurs in the industrial sector at 2022 and a large deficit occurs in the agricultural sector throughout the modeling period. The results of the modeling of the water use requirements based on historical and projected grain production indicate that the agricultural water deficit in the Haihe basin begins before the onset of the modeling period and steadily worsens through 2025. Agricultural water deficits also occur throughout the modeling period in the Huanghe and begin to occur in 1990 in the Huaihe and in 2010 in the Liaohe.

In each case in which water use requirements exceed the sustainable yield, it is assumed that the agricultural water deficit must be met by mining groundwater. For the Haihe basin, which is in an ongoing deficit situation, this assumption is confirmed by reports that groundwater mining

is already under way in the most intensely cultivated and populated areas of northern China, particularly around the Beijing area (see, e.g., World Resources Institute, 1992; Zhang Qishun and Zhang Xiao, 1995).

These results have several implications for the future of China, if the country is to remain on its current course of rapid economic growth and expanding population, including the following:

- 1) Agricultural production may need to move from the north to the water-plentiful provinces in southern China (assuming that there is land available for agriculture);
- 2) The future availability of water in the northern provinces may depend on the transfer of water from southern China and the Chang Jiang (Yangtze) (cost and feasibility will play a role);
- 3) China may need to concentrate on growing fruits and vegetables while relying on imports to satisfy growing grain requirements.

Recommendations

The analysis of China's water resources for NIC-Medea was limited to estimating the water surpluses and/or deficits by developing a model of available water through the year 2025 for five basins and generating preliminary projections of water use in each basin for the period from 1980 to 2025 on the basis of sustainable use. Recommendations, discussed below, include refining and improving the water and agronomic models and extending the models to include additional water basins. Expanding the models to incorporate input from submodels such as energy, finance, and environmental impact is also being considered.

Water Model

It is recommended that the water model be refined so that it includes all of China, quantifies groundwater storage, and includes complete data on interbasin transfers:

Extending the Model to All of China: For purposes of the NIC-Medea preliminary results, the China water model was applied to five basins representing 43% of the mean annual runoff and 73% of the arable land in China. Extending the model to "all of China" means extending the model to an additional five regions. The resulting model would represent 100% of the mean annual runoff and 100% of the arable land. This will allow for interregional comparisons of results as well as comparisons with other national data.

Quantifying Groundwater Storage: For the preliminary results, information on the quantities of river basin groundwater reserves was not available. Initially, data on the quantity of water in

each aquifer will be needed; ultimately, data on the depth and the quality of these reserves will be required. An initial survey will be performed to determine if the data exists. If the data does exist, a pilot survey for the Haihe Basin will be performed. Including quantitative information on groundwater reserves will make it possible to calculate the proportions of these reserves that are being depleted and to predict when the reserves will be unable to supply additional water.

Additional Data on Interbasin Transfers: Information on interbasin transfers used in the model was limited to the transfers of water from the Chang Jiang and Huanghe basins to the Huaihe and Haihe basins. Interbasin transfers are an important component of water supply to the northern agricultural areas. It is thus vital to the validity of the model that as complete an inventory as possible on interbasin transfer be obtained. This would include information on any existing transfers that were not accounted for in the model and information on aqueducts that are planned for future interbasin transfer. The model is programmed to access any planned future aqueducts the year that they are expected to be put into service.

Additional refinements to the China water model may include the following:

- 1) Sensitivity analyses to identify critical parameters.
- 2) The development of a component that would allow for the consideration of water quality constraints. This effort would need to address both surface water and groundwater quality. It would also require developing the model at the subbasin level because water quality problems are commonly localized. Each basin would be divided into spatial components (such as tributaries and reaches of the main river) that represent distinct hydrologic sections of the basin. Each subbasin would be represented by a unique model that would include interactions with other subbasins (in the form of water transfers). If such a component is developed, the effects of seasonality are also likely to be considered (by reducing the time step from yearly to monthly), and optimal surface water management may also be incorporated (by including reservoirs and their operating rules).
- 3) The development of more reliable water use requirements for each of the major end-use sectors: agricultural, urban, and industrial.
- 4) The improvement of return-flow algorithms to better reflect Chinese water management practices that may be specific to the three end-use sectors and their regional variations.
- 5) Augmentation of the stochastic generation of precipitation and runoff to include interbasin correlation of weather patterns and drought and flood patterns across China.

Agronomic Model

The initial objective in designing the agronomic model was to provide first-order estimates of both China's grain consumption requirements and the land area and water volumes necessary to produce those grains. The model was extended to address arable land and water resources as well as historical production levels for the five basins studied. A number of extensions and refinements are recommended to carry the model beyond a first-order prototype. The highest priority improvements would be to extend the model to all of China and to improve the computations of water use for the production of the grains.

Extending the Model to All of China: The five basins studied currently produce about 65% of China's total grain production and use about half of China's available agricultural water; a significant fraction of the totals was not accounted for within the model. Extending both the grain consumption and the production transformation segments of the agronomic model to all of China will permit a more quantitative basis for assessing land and water imbalances between the water basins and may contribute to solutions for optimizing the country's grain production.

Improving the Water Consumption Computations: Water use requirements for grain production were computed on the basis of coefficients that were calibrated using known production and water consumption values for a single year (1980) in which both sets of data were available. This approach agglomerates many variables that can individually strongly influence water consumption; for example, drought, pestilence, humidity; and soil quality and drainage. Two approaches have been proposed to address this weakness: 1) Monte Carlo estimation and 2) more elementary-level agronomic modeling. Improving the accuracy of the agricultural water consumption computations will greatly improve the model, as agriculture consumes about 70% of the total for the three end-use sectors.

The following improvements to the agronomic model are also recommended:

- 1) Completion of the region-to-basin transformation submodel;
- 2) Incorporation of grain productivity trend influences (such as agronomic research investment; pesticide and fertilizer use; and land loss due to urbanization, industrialization, and salinization); and
- 3) Refinement of the grain consumption and meat animal submodel to a) accommodate the effects of rising economic trends such as changing grain consumption patterns and increased meat consumption; b) include grain demands for exported meat animals; c) include seed grain consumption and inventory losses; d) account for fish and other seafood consumption; and e) model individual meat animal grain consumption separately.

Expanding the Models

The water and agronomic models used in this analysis were developed with an eye toward adapting the analysis of water availability and use to countries other than China and toward expanding the models to incorporate input from submodels of other critical infrastructures such as energy and finance and of environmental impacts such as global warming. The models can also be expanded to include optimization programs (which find optimal solutions, such as cost or food-shortage minimization, through multiattribute decision analysis or linear optimization). It is further recommended that uncertainty analyses and data value calculations be performed to identify where and when additional data should be collected before policy actions are initiated or modified and to track the consequences of policy decisions.

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APPENDIX A – THE CHINA WATER MODEL

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APPENDIX A – THE CHINA WATER MODEL

The China water model, a dynamic computer model of the hydrological budgetary processes in the People's Republic of China, was developed by Sandia National Laboratories to analyze China's water resources. The development of the China water model was part of an effort undertaken by the Medea group of scientists at the request of the National Intelligence Council (NIC) to improve the understanding of future grain production and consumption in China and to make a preliminary assessment of the impact of potential grain shortfalls in China on the world grain market. For purposes of the NIC-Medea preliminary results, the model was used to dynamically simulate the available water resources and expected water use in five river drainage basins located in northeastern, central, and southern China, the Chang Jiang (Yangtse River), Huanghe (Yellow River), Haihe, Huaihe, and Liaohe, through 2025.

The China water model, a mass balance model of the hydrologic cycle, was constructed to simulate connections between the natural hydrologic systems in each basin and water consumption systems incorporating water use requirements in the urban, industrial, and agricultural sectors. The model computes the effects of changes in agricultural, urban, and industrial water use requirements on the availability of water in each basin. Figure A-1 shows the movement of water in the hydrologic cycle simulated in the model.

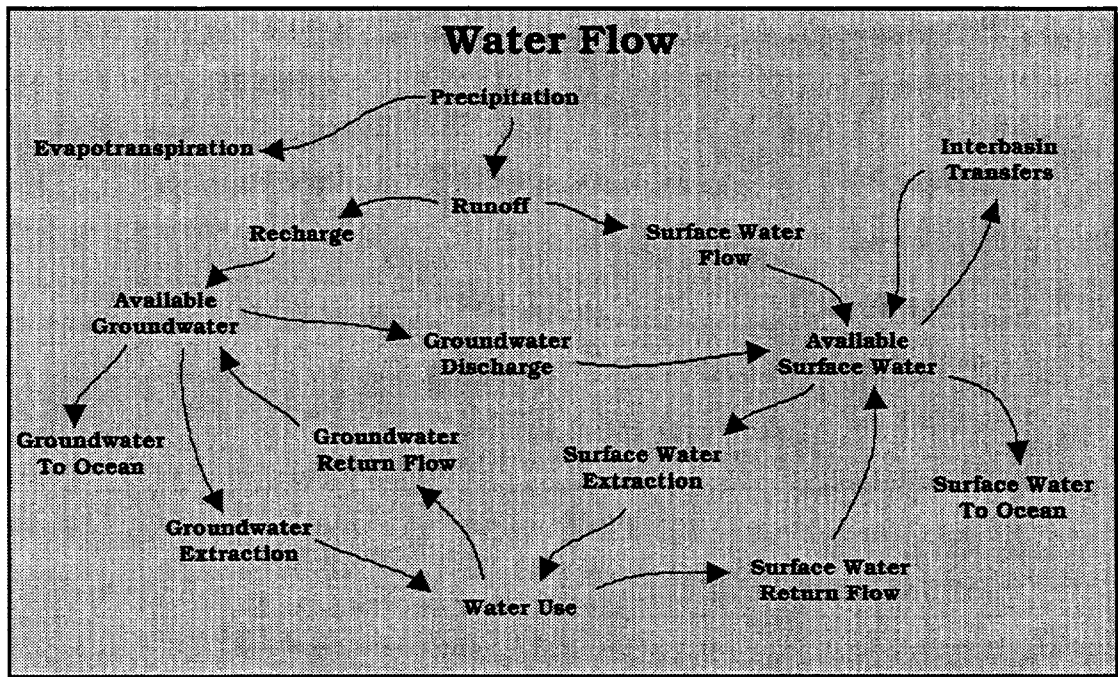


Figure A-1. Movement of water in the hydrologic cycle simulated in the China Water Model.

For purposes of the NIC-Medea preliminary results, the analysis of China's water resources included stochastic modeling of the available water in each basin through 2025 and comparison of these results with linear projections of water use in each basin to predict the total water surplus or deficit in each basin and determine the expected frequency of each basin experiencing a water deficit through 2025. The water deficit was estimated by generating 100 runs of the simulation model and computing the mean and standard deviation of the water deficit for each year through 2025.

A separate agronomic model was used to project the total agricultural use requirements for the Haihe basin through 2025. This projection was compared with the results of deterministic modeling of the water available for agriculture in the Haihe basin through 2025. In future refinements of the water model, the water model will interface directly with the agronomic model to provide for the exchange of information on projected water use requirements and available water. For purposes of the preliminary results, the output from the modeling of available water was entered manually into the agronomic model.

The Water Model

The hydrologic processes are modeled in the China water model using the PowerSim modeling system, a dynamic simulation tool that allows tracking of the flow or movement of a commodity, such as water, through time. The PowerSim system provides feedback mechanisms so that both the internal and external dynamics of the system being modeled can be simulated. In the China Water Model, the movement of water in each drainage basin was modeled by simulating changes to both the availability and use of water through time.

The model was specifically designed to:

- 1) Track the movement of water through each basin on an annual basis;
- 2) Allow the user to adjust certain major parameters affecting flow in the natural system and in a set of simple water management scenarios;
- 3) Provide an interface with the computational model so that the user can observe the simulation, modify parameters both before and during model computation, and investigate policy options.

There are two main simulation components to the China Water Model: 1) a model of the hydrologic system that quantifies the amount of extractable water available within each water basin and 2) a model for water use requirements. The hydrological model covers the main components of the hydrologic cycle—precipitation, surface water, and groundwater—and the

movement of water to and from these components via runoff, groundwater recharge, groundwater discharge, evapotranspiration (direct evaporation and evaporation through plants), discharge to the ocean (from both surface water and groundwater), and the transfer of water from one basin to another by way of canal (interbasin transfers). The water-use component of the model covers the extraction of water from both surface water and groundwater and its division between the agricultural, industrial, and urban sectors. Total available water and total water use requirements can then be compared to determine the likelihood of each basin's water needs being met.

The model can be adjusted using simulation controls as follows:

1) *Deterministic versus stochastic switch*: In the deterministic setting, average annual precipitation and average annual runoff is used in each time step. In the stochastic setting, a series of correlated random values are generated for annual rainfall and runoff using a normal distribution and the mean and standard deviation of these parameters.

2) *Water-use requirements – slope delta slider bars*: Users can adjust the slope of the water-use requirements curves for each basin and for each use sector: agricultural, urban, and industrial.

3) *Return flow – slider bars*: Users can adjust the percentage of return flow from each sector for each basin.

Data

Data for the water model was obtained from several sources, as follows:

1) Data was collected, translated, and summarized from Chinese government agency publications and maps by Jim Nickum, one of the study team members, who traveled to China during August and September 1996.

2) Data was also obtained from *Water Resources Assessment for China* (Department of Hydrology, Ministry of Water Resources, 1992), which was loaned to the study team by Jim Condon of the Defense Intelligence Agency.

3) Spatial data was obtained from the Consortium for International Earth Science Information Network (CIESIN) and the Australian Centre of the Asian Spatial Information and Analysis Network (ACASIAN).

The following data elements were used to simulate the hydrological processes: precipitation, total evapotranspiration, surface water runoff, interbasin transfers, ocean discharge (average and

minimum), groundwater recharge, groundwater extraction, surface water extraction, and water-use requirements. A summary of the data elements used and their sources appears in Table A-1.

Precipitation Data

Annual precipitation and mean annual discharge are the primary drivers for the hydrologic portion of the model. Average annual precipitation and an approximation of the standard deviation of average annual precipitation are used to randomly generate a time series of annual precipitation.

Table A-1. Sources for Hydrological Data Used in the China Water Model*

Data Element	Source
Precipitation – Average	<i>Water Resources Assessment for China</i> , Table 3-1
Precipitation – Maximum, Minimum, and Standard Deviation	<i>Map Collection of China's Climatic Resources</i>
Evaporation – Distribution	<i>Water Resources Assessment for China</i> , Table 2-18
Evaporation – Annual	<i>Water Resources Assessment for China</i> , Figure 2-19
Surface Water – Initial Storage	<i>Almanac of China Water Resources 1991</i>
Surface Water – Basin Transfer	<i>Water Resources Utilization in China</i>
Groundwater Recharge Rate	<i>Water Resources Assessment for China</i> , Table 4-15
Ocean Discharge	<i>Water Resources Assessment for China</i> , Table 3-24
Ocean Discharge – Minimum	<i>Water Resources Utilization in China</i>
Urban, Industrial, and Agricultural Water Supply and Use Requirements	<i>Water Resources Utilization in China</i>
Agricultural Return Flow	<i>Dr. John Hernandez, New Mexico State University (1997)</i>
Spatial Data – City Locations, Province Boundaries	<i>Consortium for International Earth Science Information Network (CIESIN)</i>
Spatial Data – River Basin Delineation	<i>Australian Center of the Asian Spatial Information and Analysis Network (ACASIAN)</i>
* See the References section for a complete listing of these sources.	

Average Annual Precipitation

Average annual precipitation was obtained from Table 3-1 in *Water Resources Assessment for China*. The standard deviation for annual precipitation was computed from mean annual precipitation and a coefficient of variation for precipitation that was assumed to be equal to the coefficient of variation computed for mean annual runoff.

Surface Water Data

Surface water discharge: Annual averages for surface water runoff for each basin are from Table 3-3 in *Water Resources Assessment for China*. Table A-2 presents the annual averages and the standard deviations derived from these values.

Table A-2. Surface Water Runoff

Basin	Average Annual Flow (10⁹ m³)	Derived Standard Deviation (10⁹ m³)
Haihe	28.8	13
Huaihe	74.1	36
Huanghe	66.1	14
Chang Jiang	951	140
Liaohe	48.7	16

Return Flow: A return flow of 40% for the agricultural sector was based on the assumption that at least one-third of the water applied to the crop will be returned and the other two-thirds is lost to evapotranspiration. A minimum of one third of the water is needed to flush salts from the system (Hernandez, 1997); 40% was thus used as a conservative estimate. A return flow of 50% for the urban sector is based on the return flow percentage for water to U.S. municipalities. A return flow of 10% for the industrial sector is based on the assumption that most industries will reuse their water until it is virtually used up, leaving very little return flow (Hernandez, 1997).

Interbasin Transfer: Values for interbasin transfer in Table A-3 were derived from a summary by Jim Nickum of information from *Water Resources Utilization in China*. This data showed a slight decline in transfer rates from Huanghe to Haihe and Huaihe between 1980 and recent years, but no apparent decline in the transfer from Chang Jiang to Huaihe. In the absence of any additional data, the transfer amount from Huanghe was divided equally between Haihe and Huaihe. The decline is not incorporated into the model.

Table A-3. Interbasin Transfer Rates

From	To	Amount of Transfer (10⁹ m³)
Huanghe	Haihe & Huaihe	9.1
Chang Jiang	Huaihe	10.1

Ocean Discharge: The values for ocean discharge (Table A-4) are allowed to fluctuate in the model but are compared to the historical mean and are constrained by minimum discharges needed to flush silt into the sea.

Table A-4. Basin Discharge to the Sea

Basin	Annual Mean Discharge to Sea (10⁹ m³)	Minimum Discharge to Flush Silt (10⁹ m³)
Haihe	16	8
Huaihe	59.3	NA
Huanghe	41	20
Chang Jiang	890.8	NA
Liaohe	21.3	NA

Groundwater Data

Recharge to Groundwater: Values used to compute groundwater recharge for each basin (Table A-5) were based on values defined as the total groundwater recharge for the plains areas within each basin or region (from Table 4-15, *Water Resources Assessment for China*). Base flow from the mountains was not included in these recharge values.

Table A-5. Groundwater Recharge

Basin	Recharge (Plains) (10⁹ m³)
Haihe	19.23
Huaihe	30.67
Huanghe	31.32
Chang Jiang	26.09
Liaohe	11.04

Groundwater and Surface Water Extraction: The initial values for groundwater and surface water extraction are based on the groundwater and surface water use values for 1980 presented in *Water Resources Utilization in China*. Projected values are based on a linear relationship between the 1980 water use values (Table A-6) and estimated values for the year 2000 (Table A-7).

Table A-6. 1980 Water Use in Five Chinese Water Basins

Basin	Source (10 ⁹ m ³)			Use (10 ⁹ m ³)			
	Surface	Ground	Total	Urban*	Industry	Agriculture	Total
Liaohe	10.48	4.84	15.31	0.78	3.01	11.53	15.31
Haihe	18.14	20.24	38.38	2.57	4.87	30.94	38.38
Huaihe	40.23	12.89	53.13	3.25	3.84	46.03	53.13
Huanghe	27.40	8.44	35.84	1.61	2.79	31.44	35.84
Chang Jiang	128.63	6.70	135.33	9.72	20.88	104.73	135.33

* Urban includes rural drinking water.

Table A-7. Projected Water Capacity & Use Requirements for the Year 2000 by Sector

Basin	Available Water (10 ⁹ m ³)			Use Requirements (10 ⁹ m ³)				Deficit (10 ⁹ m ³)
	Surface	Ground	Total	Urban*	Industry	Agriculture	Total	
Liaohe	16.9	7.87	24.76	3.08	8.28	17.85	29.20	4.44
Haihe	22.37	17.56	39.93	6.00	10.01	36.25	52.26	12.33
Huaihe	58.53	16.05	74.58	5.62	14.43	62.31	82.36	7.78
Huanghe	32.01	8.99	41.00	2.91	7.87	32.44	43.22	2.22
Chang Jiang	236.22	7.58	243.79	23.93	57.81	169.97	251.71	7.91

* Urban includes rural drinking water.

Modeling of Available Water and Projections of Water Use

The total available water is calculated in terms of potentially extractable groundwater and surface water by simulating the hydrologic balance within each basin. The water model, schematically represented in Figure A-2, is driven by precipitation, runoff, and water use requirements.

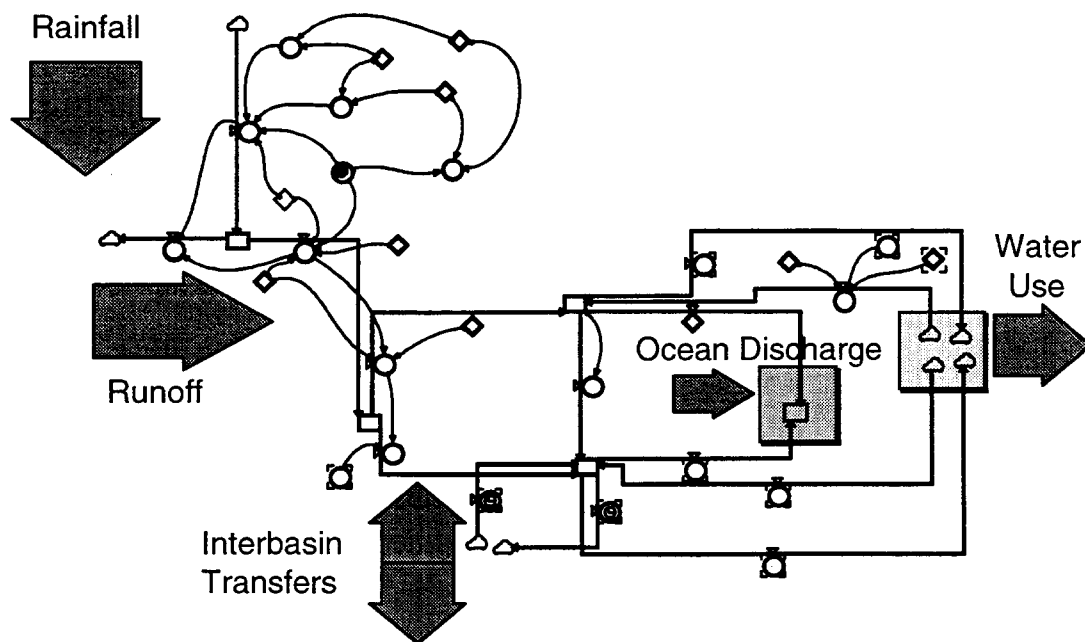


Figure A-2. Overview schematic representation of the China water model.

Available Water

Rainfall, Runoff, and Evapotranspiration: The model can be run either in a deterministic mode, in which annual averages for rainfall and runoff are used, or in a stochastic mode, in which the mean and standard deviation of each of these parameters are correlated to produce random time series of both rainfall and runoff. A time series of total evaporation, which includes evaporation from water bodies, evapotranspiration, and groundwater evaporation, is simulated by subtracting runoff from rainfall. These values are then checked for reasonableness against values of annual average total evaporation. Runoff is then apportioned between groundwater recharge and surface water flow. Figure A-3 shows a schematic representation of the rainfall/runoff portion of the water model.

Groundwater Recharge and Surface Water Flow: Groundwater recharge and surface water flow are calculated in the following manner. Groundwater recharge is computed in proportion to

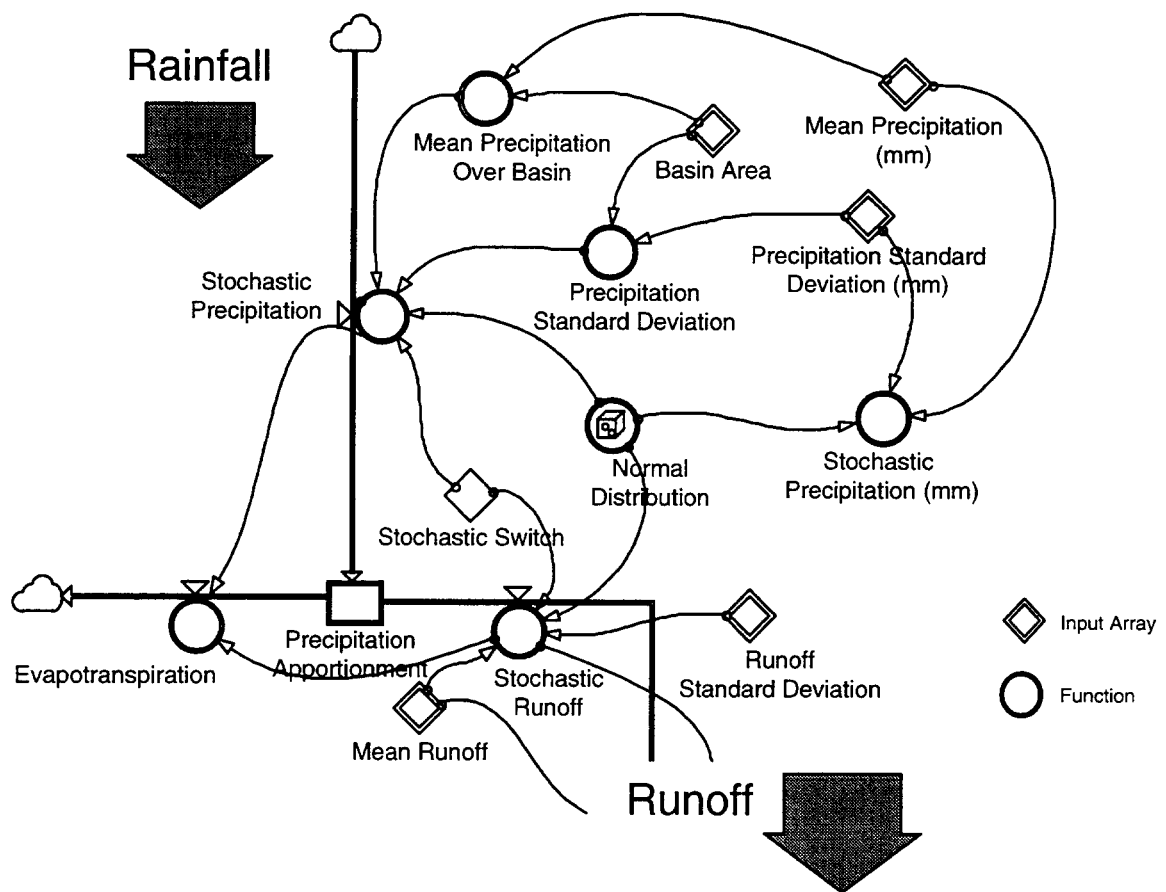


Figure A-3. Schematic of the rainfall/runoff portion of the China water model.

average runoff and average recharge values (from *Water Resources Assessment for China*); surface water flow is the remainder.

The Quantity of Potentially Extractable Water: The potential water supply is a function of mass balance considerations and is equal to the inflows to each basin's hydrologic system minus the outflows. Figure A-4 shows a schematic representation of the elements involved in the computation of available surface water and available groundwater in the model. Groundwater recharge and surface water flow plus any return flows constitute the inflows, while discharges to the ocean and consumption constitute the outflows. Water transfers between basins can be either inflows or outflows depending on the direction of the transfer. (Outflows due to evapotranspiration are accounted for prior to this point in the model.) The potential drought-mitigating effects of surface water storage in reservoirs are not included in the model because stored water is considered more important for evening out seasonal variations in precipitation than for evening out year-to-year variations. Although water supplied from reservoir storage may turn out to be nonnegligible in forestalling drought over a time frame of a year or two, limited quantities of water held in surface water storage become relatively inconsequential over the long

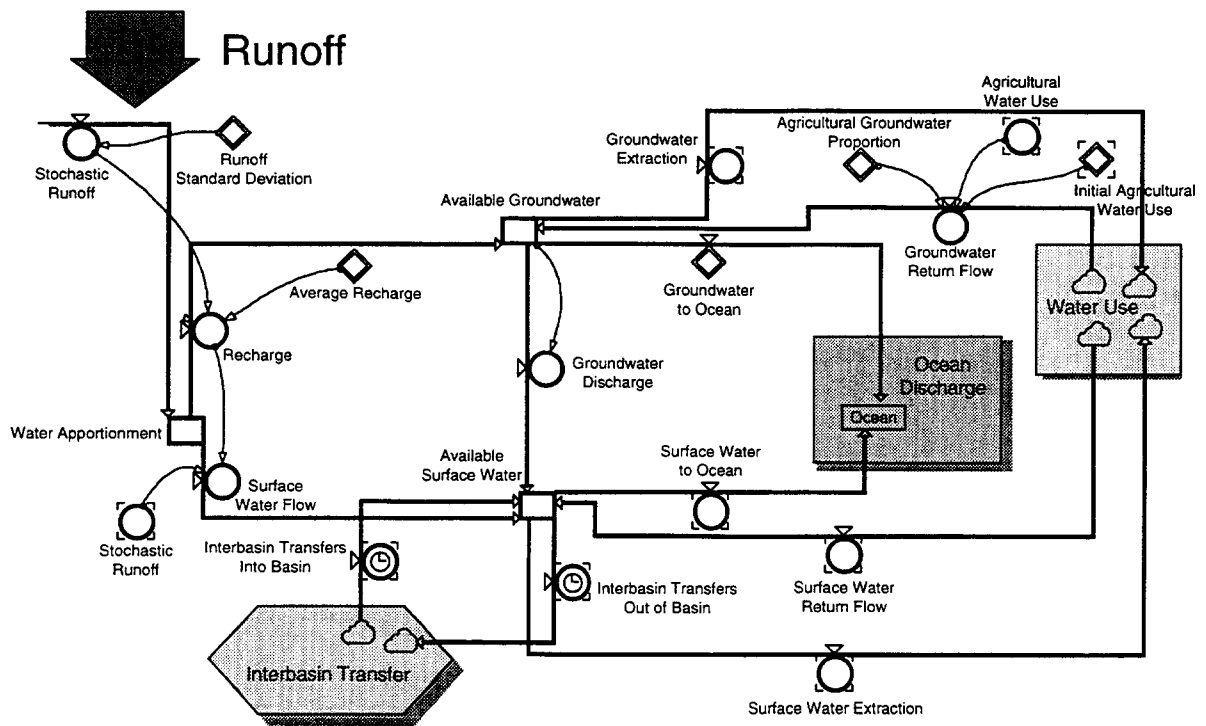


Figure A-4. Schematic representation of the China water model showing the elements involved in the computation of available surface water and available groundwater.

term once the requirements for water consistently exceed the extractable amount. Moreover, temporal correlation in annual precipitation is not included; therefore, drought years are typically simulated as isolated events. If droughts were realistically simulated (i.e., extending over several years), then the limited surface water storage in reservoirs would surely be depleted.

Surface Water and Groundwater Extraction: Extraction from groundwater is constrained to not exceed an amount equal to the average recharge plus agricultural return flows to the groundwater system minus any groundwater discharges to the ocean that may be required to prevent salt water intrusion. Groundwater extraction below this amount occurs at a proportion to surface water extraction equivalent to the 1980 proportion. Any unused groundwater is discharged to the surface water system. It is assumed that when water use requirements exceed sustainable water supply, groundwater mining will occur. The mining of groundwater is not accounted for because estimates of groundwater reserves were not obtained. Similarly, the depletion of economically recoverable groundwater reserves could not be computed. Groundwater mining is already under way in Haihe, particularly around the Beijing area, and in other parts of northern China (see, e.g., Zhang Qishun and Zhang Xiao, 1995). Groundwater mining cannot continue indefinitely, but is limited to the extent and availability of water in the aquifer. In most situations, groundwater mining will continue until the cost of further extraction

is no longer economical. In these cases, the users will be forced to return to extracting water at the sustainable yield.

Extraction from available surface water is equal to the difference between the total amount of water to be extracted and that supplied from groundwater, if the water use requirements do not exceed the total available surface water. If the water use requirements exceed the amount of available surface water and the sustainable yield of groundwater, all available surface water will be extracted (all inflows minus any interbasin transfers out and the minimum required surface water discharge to the ocean). Any unused water is discharged to the ocean. See Figure A-5, a schematic representation of the China water model showing the elements involved in the computation of extractable surface water.

Water Use Requirements

Water use requirements for each basin were projected using a linear function based on values for 1980 water use and for expected water use in the year 2000. The data was obtained from the Ministry of Water Resources in Beijing (*Water Resources Utilization in China*). The values appear in Tables A-6 and A-7. A water use priority scheme was imposed as follows: Urban sector requirements were met first, industrial requirements were met second, and agricultural requirements received the lowest priority. See Figure A-6 for a schematic representation of the

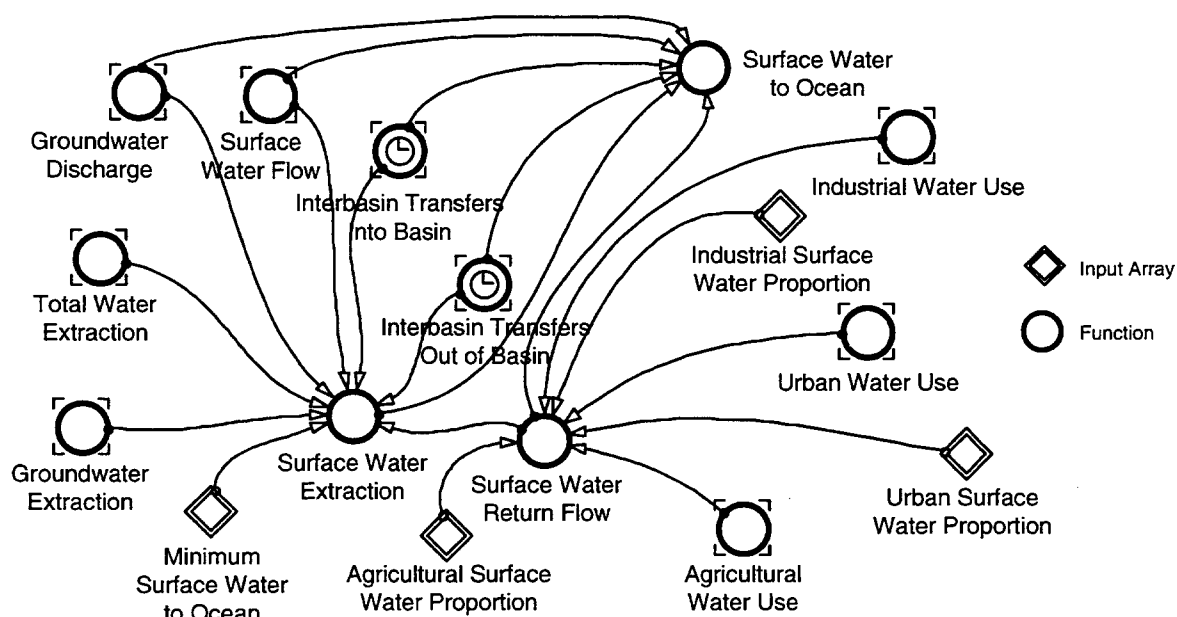


Figure A-5. Schematic of the China water model showing the elements involved in the computation of extractable surface water.

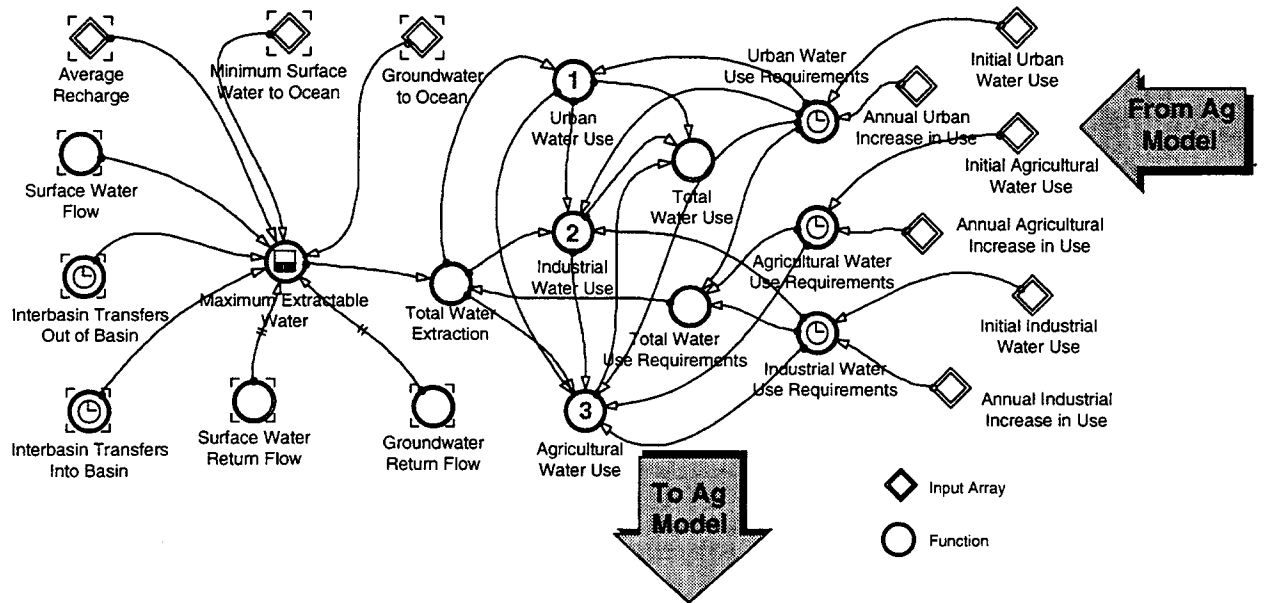


Figure A-6. Schematic of the China water model showing the elements involved in the computation of the maximum amount of extractable water, water use requirements per sector, and water use per sector.

China water model showing the elements involved in the computation of the maximum amount of extractable water, water use requirements per sector, and water use per sector. Note the arrows “From Ag Model” and “To Ag Model” in the figure, showing the planned interface with the agronomic model.

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APPENDIX B – THE CHINA AGRONOMIC MODEL

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APPENDIX B – THE CHINA AGRONOMIC MODEL

The China agronomic model is a component of the China water model, a dynamic computer model of the hydrological budgetary processes in the People's Republic of China developed by Sandia National Laboratories to analyze China's water resources. The development of the China water model was part of an effort undertaken by the Medea group of scientists at the request of the National Intelligence Council (NIC) to improve the understanding of future grain production and consumption in China and to make a preliminary assessment of the impact of potential grain shortfalls in China on the world grain market. For purposes of the NIC-Medea preliminary results, the China water model was used to dynamically simulate the available water resources and expected water use in the urban, industrial, and agricultural end-use sectors in five river drainage basins located in northeastern, central, and southern China, the Chang Jiang (Yangtse River), Huanghe (Yellow River), Haihe, Huaihe, and Liaohe, through 2025.

The China agronomic model was specifically designed to:

- Generate projections of the water required to service China's agricultural sector;
- Generate projections of each water basin's contribution to China's total agricultural production; and
- Compare China's projected grain production with projected grain consumption to estimate any grain surplus and/or deficit.

The agronomic model was designed to interface bidirectionally with the China water model to provide for the exchange of information on projected water use requirements and available water. The agronomic model would provide computed values for agricultural water use requirements to the water model for use in the water balance computations and receive in return computed values for available water to project water-constrained agricultural production levels. At the time that the NIC-Medea preliminary results were generated, however, the interface had not yet been completed, and it was necessary to enter output on water available for agriculture generated by the water model into the agronomic model manually.

The China agronomic model has two segments, a grain demand segment and a region-to-basin transformation segment. The grain demand segment, schematically represented in Figure B-1, computes 1) a population-driven all-China projected grain demand by weight for

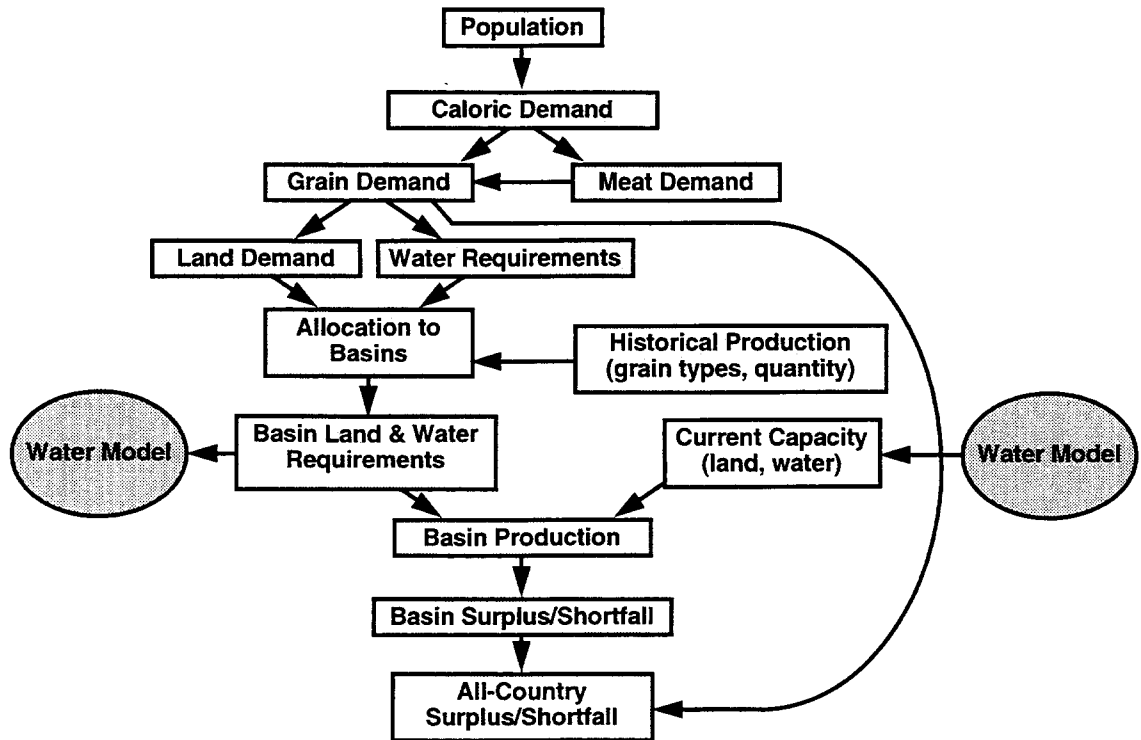


Figure B-1. The grain demand segment of the China agronomic model.

each grain type for each year and 2) the water volume necessary to produce the grain to meet that demand using water coefficients for each grain type. The region-to-basin transformation segment of the model, represented in Figure B-2, was used for the NIC-Medea preliminary results to convert Chinese regional grain production data from the U.S. Department of Agriculture/Economic Research Service (USDA/ERS-730) to provincial then to water basin grain production data and to compute the projected agricultural water requirements for each basin. This conversion was required because the simulation focused on hydrological budgetary processes in major river drainage basins rather than regions or provinces, and, to be of use in the model, it was necessary to map the USDA/ERS regional data to the water basins.

Note that the USDA/ERS regional grain production data used to generate the agricultural water requirements for the NIC-Medea preliminary results ran from 1980 through 2010. The agricultural water requirements were generated in the model to 2010 and then extrapolated to 2025. The projection of available water for the Haihe basin was deterministically generated in the water model, and this output was entered into the agronomic model manually.

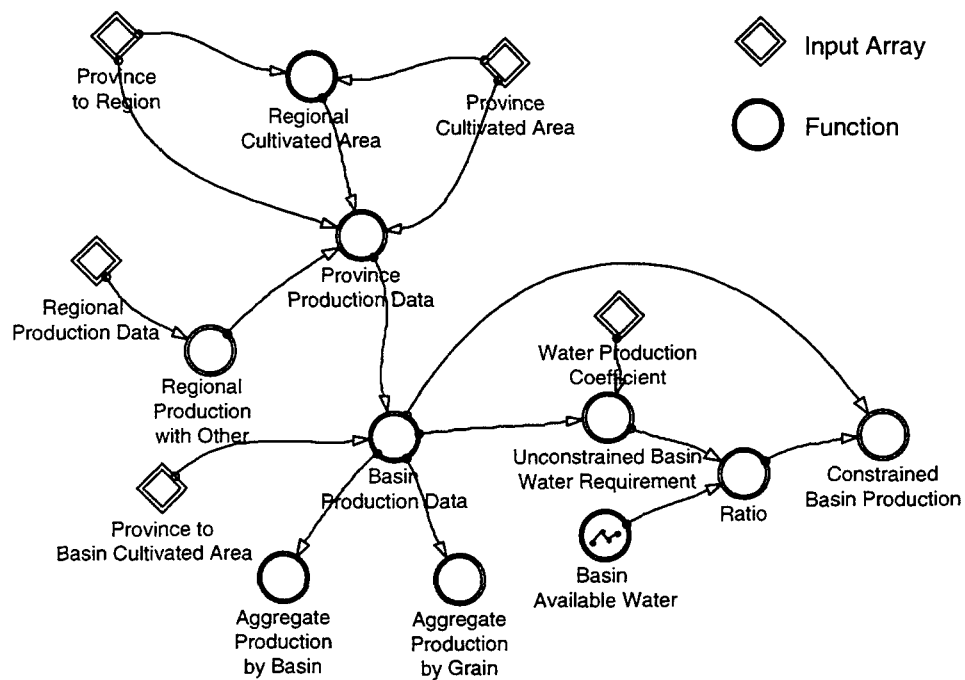


Figure B-2. The region-to-basin transformation segment of the China agronomic model.

Grain Demand Segment

The grain demand segment of the agronomic model is population driven, that is, the all-China food requirement is computed on the basis of population growth, average annual per capita caloric demand, and the caloric content per gram of grain, as follows:

- 1) The projected yearly caloric demand for all of China is first generated by multiplying an average annual per capita caloric demand by the population size for each year in the projection. Two options are provided for entering population growth into the model: a) a standard exponentially increasing constant-annual-percentage-rate method, and b) an annually varying percentage rate method. The second method was provided to permit use of population projections corresponding with those made by the United Nations and the USDA. (United Nations/Department for Economic and Social Information and Policy Analysis, 1993; Crook and Colby, 1996). The projected yearly caloric demand for all of China is generated by multiplying an average annual per capita caloric demand by the population size for each year in the projection. The value used for daily caloric demand

was 2250 calories per capita, the median of the accepted range for the US: 2000-2500 calories per capita per day.¹

- 2) The model then apportions the all-China projected caloric demand for each year between the three major grains (rice, wheat and corn), meat, and “other” (which includes other grains and fruits and vegetables) in accordance with Chinese historical grain and meat consumption patterns from the USDA (USDA/ERS-730). To account for the caloric inefficiency of meat production, the caloric demand value apportioned to meat consumption is converted to grain-equivalent caloric demand using a grain-to-meat ratio coefficient of 4:1.² The assumption was made that, in the aggregate, meat animals consume grains and grain equivalents in the following proportions: rice–15%, wheat–15%, corn–50%, and other–20%. The adjusted grain-equivalent caloric demand values are then multiplied by human meat consumption caloric demand, and the resulting values are added to the corresponding human grain caloric demand to obtain the all-China total grain caloric demand for each grain type, in billions of calories.
- 3) The total projected yearly all-China demand by weight for each grain type³ is obtained by dividing the total grain caloric demand for each grain type by a coefficient in calories per gram corresponding to the average caloric content for each grain type as follows: rice–3.63, wheat–3.35, corn–3.65, other–3.54, and meat–3.48. These values were obtained from the *USDA Nutrient Database for Standard Reference* (1997).
- 4) Estimates of the total land required to produce the grain to meet the total projected yearly demand are calculated as follows: The all-China yearly demand values by weight for each grain type are divided by the corresponding yield coefficients obtained from the USDA (USDA/ERS-730) (in metric tons per hectare): rice–4.1, wheat–3.41, corn–4.74, and other–4.0 (an intermediate value). It is assumed that factors for same-grain multiple-cropping have been implicitly captured in the yield coefficients to the first order; future refinements to the model are planned for computations for multiple-cropping of different grains.

¹ This figure will be revised when a better estimate becomes available.

² Meat animals are inefficient producers of calories for human consumption. For example, seven kilograms of grain equivalents are required to produce one kilogram of beef, and two kilograms of grain are required to produce one kilogram of poultry (see *The Economist*, November 16, 1996). The ratio of 4 kilograms of grain equivalents to one kilogram of meat is an intermediate value between the values for beef and poultry. It was used in the model as an aggregate approximation for all meat consumed in China. This value will be disaggregated into individual meats in future refinements of the model.

³ As a validity check, these totals were divided by the total population to obtain per capita consumption figures and were compared with historical data.

- 5) The water volume necessary to produce the grain to meet the total projected yearly demand by weight for each grain type is computed by multiplying the total projected yearly demand by weight for each grain type by the corresponding water coefficient (in cubic meters of water per kilogram of grain). Water coefficients in this form are not readily available from the agronomic community because of inherently large variances caused by regional differences in factors such as soil composition and porosity and evapotranspiration rates. Plans are under way to address this issue with Monte Carlo methods for the longer term, but for the present the issue has been addressed by calibrating the water coefficients against known water consumption levels and known grain production levels for a specific year in which both sets of data are available. This computation is described in the next section, *Region-to-Basin Transformation Segment*. The resulting coefficients used to compute the all-China agricultural water requirement were (in cubic meters per kilogram of grain): rice–1.85, wheat–1.33, corn–0.69, other–1.01. The water coefficients thus “calibrated” are presumed to be acceptable for all years for which the model is run.
- 6) Once the population-driven all-China grain demand is computed, the next step is to allocate this demand among the water basins in order to assess their ability to meet the demand with the land and water resources available within each basin. The all-China demand was allocated among the basins by prorating this demand according to the ratio of the basin’s historical production of each of the grains to the all-country historical production of each of the grains. For simplicity, a first-order approximation of historical production has been chosen to be that of the year 1990. The all-country production for the year 1990 was obtained from USDA/ERS-730. The source of the corresponding 1990 basin production is more complicated; its derivation is described below in *Region-to-Basin Transformation Segment*.
- 7) Next, the demand allocations for the basins under consideration are computed using the basin historical production figures generated. The basin cultivated land requirements are computed by dividing, as for all of China, the yields per hectare for each grain that were obtained from USDA/ERS-730 into the respective grain demands. These land requirements, summed over all grains for a basin, provide that basin’s total cultivated land area requirement. Similarly, the basin’s total agricultural water requirement is obtained by multiplying and summing over all grains the basin’s demand allocation for each grain times its respective grain production water coefficient. At this point, graphs can be produced by the model to show how well each of the basins is likely to fare over future years in producing its allocation of the all-China grain demand, within the

constraints of its available arable land and agricultural water. To accomplish this, the available agricultural water for each basin, by year, is drawn from the water model. The source of the basin available arable land is described in the following section, *Region-to-Basin Transformation Segment*.

- 8) The final step in the grain demand segment of the model is to compare the sum of all basin production for each grain with the all-China demand for each grain. This step will be completed when all of the water basins in China are modeled.

Region-to-Basin Transformation Segment

There are three purposes for the region-to-basin transformation segment of the China agronomic model. The first purpose is to transform the regional grain production data for China provided by the USDA/ERS to water basin grain production data. Converting this data provides estimates of historical basin production that can be used in the grain demand segment of the agronomic model to permit allocation of the all-China grain demand among the basins. The second purpose of the region-to-basin transformation segment is to determine the potential effects of placing basin constraints on agricultural water availability on each basin's grain production capability. The third purpose is to assess the magnitude of basin agricultural water surpluses or deficits when the basins are producing grain at officially projected levels.

The conversion of regional grain production data to water basin production data was accomplished as follows:

- 1) First, an array was developed that defined the relationship between regions and provinces (based on information provided in an e-mail from W.H. Colby, USDA/ERS, to D. Jeppesen, SNL, February 11, 1997). An array of provincial cultivated areas was then developed on the basis of data from the USDA/ERS (Crook and Colby, 1996). These two arrays, when multiplied together and summed by region, produce an array of cultivated areas for each region. An array of regional production data for each of the grains is then introduced. For the NIC-Medea preliminary results, this array was based on grain production data from 1980 to 2010 from the USDA/ERS Country Projection and Policy Analysis (CPPA) Model (*Medea Project (2/10/97): LOTUS Spreadsheet*). Provincial production data for each grain is then estimated by multiplying the array of data for regional production of each grain by the corresponding ratio of the provincial cultivated area to the cultivated area of the regions that contain the province.

- 2) An array that defines the relationship between provinces and water basins is introduced next. Unlike the array that relates intact provinces to regions (described above), this array must account for portions of provinces that lie within more than one water basin. To create this province-to-basin array, a geographical information system analysis was performed on the basis of soil geology and land slopes and was used to map the provincial cultivated areas to the appropriate water basins. Multiplying the resulting array by the provincial production data array produces an array of production data for each of the grains for each basin.
- 3) Once the basin production data for each grain type have been obtained, the next step is to assess the potential effects of placing constraints on the water available for agriculture on the grain production within each basin. This requires the development of water coefficients (see discussion in the *Grain Demand Segment* section, above). Estimates of the coefficient ranges for each of the grains were provided by Dr. Joe Ritchie, Professor of Agronomy at Michigan State University. Mean values for each grain were drawn from these ranges and used as the basis for calibrating refined water coefficients using 1) agricultural water consumption data for the five basins for the year 1980 from *Water Resources Utilization in China* and 2) grain production data for the five basins for the year 1980 from the array computations described above. See the *Grain Demand Segment*, above, for the resulting calibrated coefficient values.
- 4) The array of basin production data for each grain is next multiplied by the array of water coefficients. By summing this array over all grains for each basin, the “unconstrained basin water requirement” for each basin is obtained. This is the amount of water required to produce the total grain demand that has been assigned to that basin. A water “ratio” is then computed for each basin by dividing the unconstrained basin water requirement into the amount of water available for agriculture for that basin, which is obtained from the China water model. Finally, the water-constrained production for each basin for each grain is obtained by multiplying this “ratio” array by the basin production data array. The unconstrained basin water requirement and the water available for agriculture for a given basin can be plotted on the same chart to show the sustainable-yield water deficit.

Note that all of the procedures described above are repeated for each year in the simulation. In the grain demand segment, the simulation begins with a population that increases every year; in the region-to-basin transformation segment, the simulation begins with regional production that changes each year.

Data

The following data elements were used in the China agronomic model: population growth rate; caloric content of grains; grain-to-meat conversion efficiencies; grain yields per hectare; grain consumption requirements; grain production and consumption; agricultural water availability; grain water consumption coefficients; provincial cultivated areas; and province-to-region relationships. A summary of the data elements used and their sources appears in Table B-1.

Table B-1. Sources of Data for the China Agronomic Model*

Data Element	Source
Population Growth Rate	<i>The Future of China's Grain Market</i> , USDA/ERS-730 <i>World Population Prospects</i> , United Nations
Caloric Content of Grains	<i>USDA Nutrient Database for Standard Reference</i>
Grain-to-Meat Conversion Efficiencies	<i>Will the World Starve?</i> , The Economist, November 16, 1996 <i>Chinese Grain Economy and Policy</i> , CAB International
Grain Yields per Hectare	<i>The Future of China's Grain Market</i> , USDA/ERS-730
Grain Consumption Requirements, Production, and Consumption	<i>The Future of China's Grain Market</i> , USDA/ERS-730 <i>Chinese Grain Economy and Policy</i> , CAB International <i>Medea Project (2/10/97): LOTUS Spreadsheet from USDA/ERS CPPA Model</i>
Agricultural Water Availability	<i>Water Resources Utilization in China</i>
Grain Water Consumption Coefficients (Estimated Ranges)	<i>Dr. Joe Ritchie, Department of Agronomy, Michigan State University, 1997</i>
Provincial Cultivated Areas	<i>The Future of China's Grain Market</i> , USDA/ERS-730
Province-to-Region Relationships	<i>W. Colby, USDA</i>
* See the References section for a complete listing of these sources.	

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APPENDIX C – NIC-MEDEA CHINA WATER MODEL ADDITIONAL PRELIMINARY RESULTS

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APPENDIX C – NIC-MEDEA CHINA WATER MODEL ADDITIONAL PRELIMINARY RESULTS

Figures C-1 through C-5 present the results of a single run of the China water model through the year 2025 for the Haihe, Huanghe, Huaihe, Liaohe, and Chang Jiang, respectively. As indicated in Figures C-1, C-2, and C-4, when the total water requirements for a basin exceed the combined total of sustainable water available from both surface water and groundwater, a deficit results. These results indicate that the Chang Jiang basin (Figure C-5) will have a substantial surplus of water through 2025 and that the Haihe basin (Figure C-1) is in an ongoing deficit situation. The other three basins generally fall between these two extremes.

Figures C-6 through C-10 present the predicted water deficits or surpluses for the Haihe, Huanghe, Huaihe, Liaohe, and Chang Jiang basins, respectively, through the year 2025 estimated by generating 100 runs of the simulation model and computing the mean and standard deviation of the water deficit for each year through 2025. Based on the assumptions used in the simulation, there is a probability of 0.68 that the actual water deficit for each basin will lie between the upper and lower curves in each figure.

Figures C-11 through C-15 present the results of single runs of the China water model through the year 2025 for the Haihe, Huanghe, Huaihe, Liaohe, and Chang Jiang basins, respectively, showing the water use by sector and water deficits. As indicated in Figure C-11, the urban water requirements for the Haihe basin are met through the year 2025. A small deficit occurs in the industrial sector at 2022, and a large deficit occurs in the agricultural sector throughout the modeling period that steadily worsens through 2025. Figure C-12 indicates that, although the water requirements in the urban and industrial sectors in the Huanghe basin are met through the year 2025, water deficits occur in the agricultural sector throughout the modeling period. Water requirements in the urban and industrial sectors are also met in the Huaihe and the Liaohe basins through 2025, as shown in Figures C-13 and C-14, but small water deficits begin to occur in the agricultural sector beginning in 1990 in the Huaihe and in the agricultural sector in the Liaohe basin after 2010. Finally, as shown in Figure C-15, the urban, industrial, and agricultural requirements are all met in the Chang Jiang basin through the year 2025.

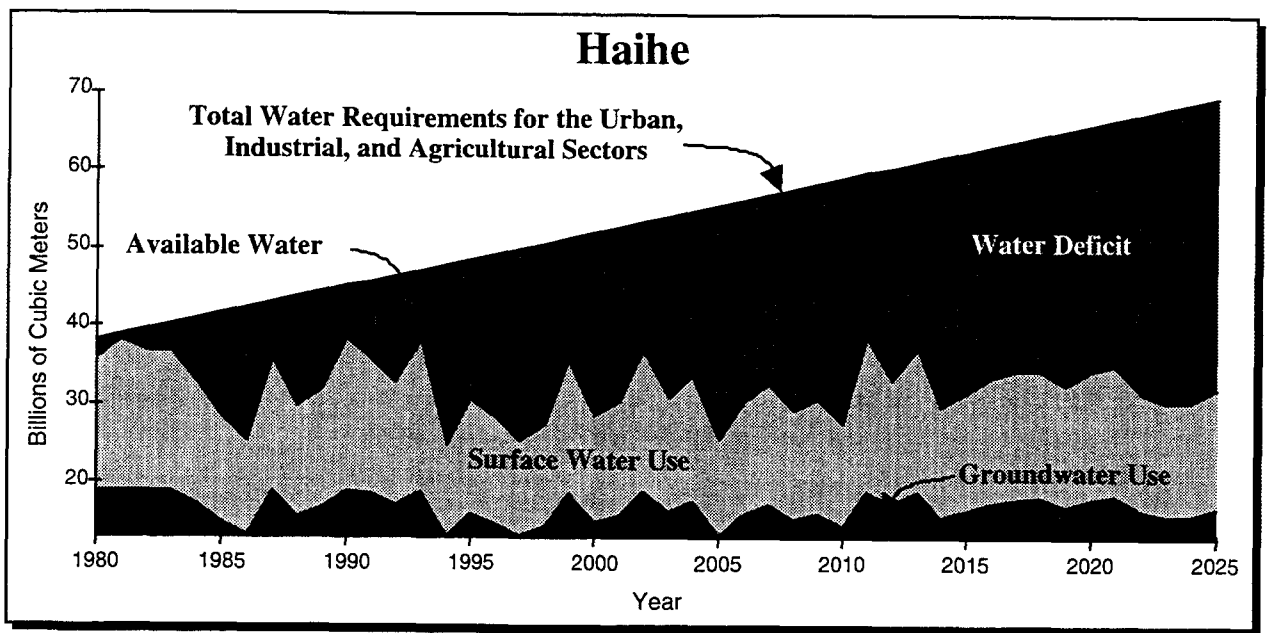


Figure C-1. Comparison of the results of a single run of stochastic modeling of available water with linear projection of total water requirements in the Haihe Basin.

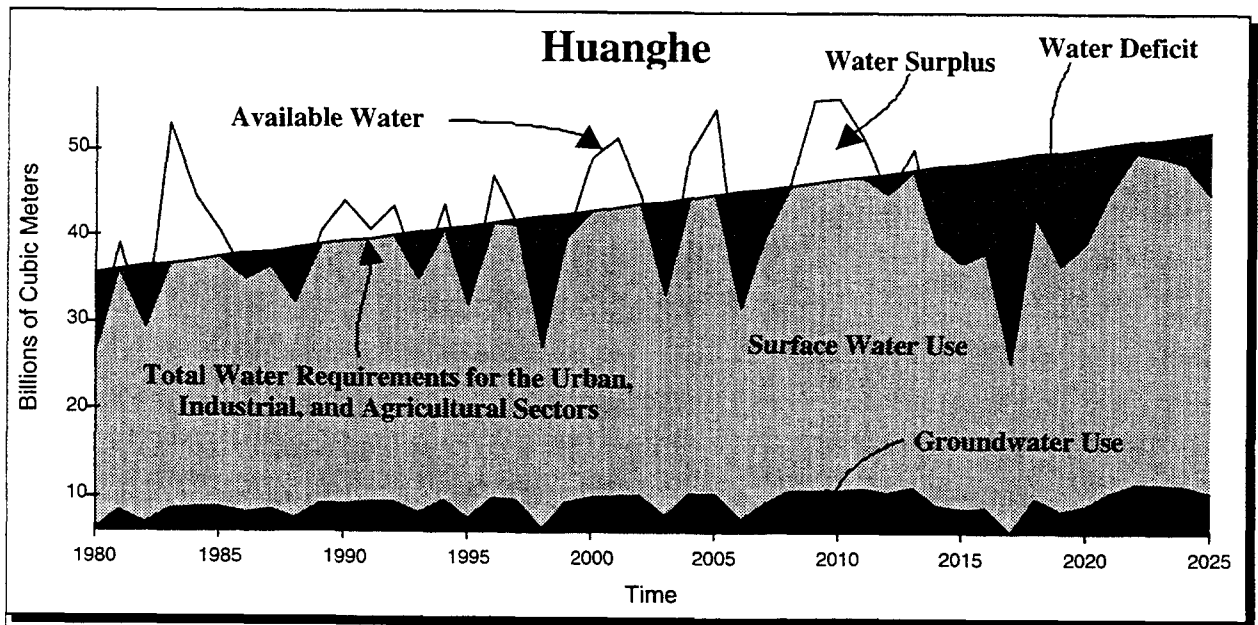


Figure C-2. Comparison of the results of a single run of stochastic modeling of available water with linear projection of total water requirements in the Huanghe Basin.

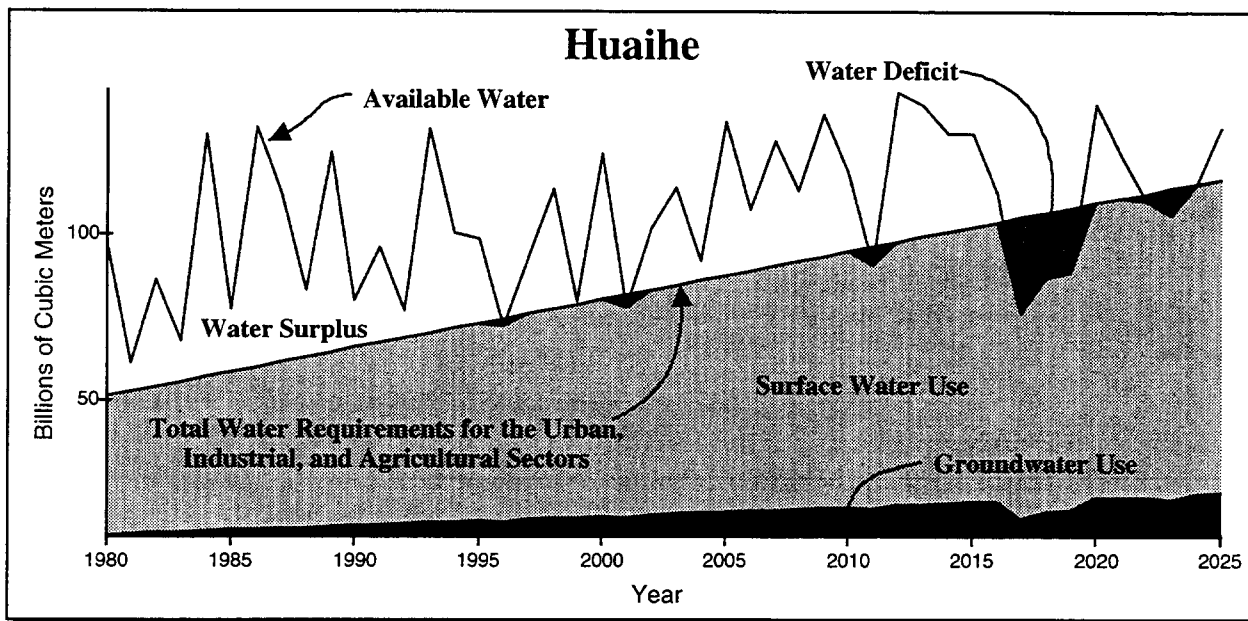


Figure C-3. Comparison of the results of a single run of stochastic modeling of available water with linear projection of total water requirements in the Huaihe Basin.

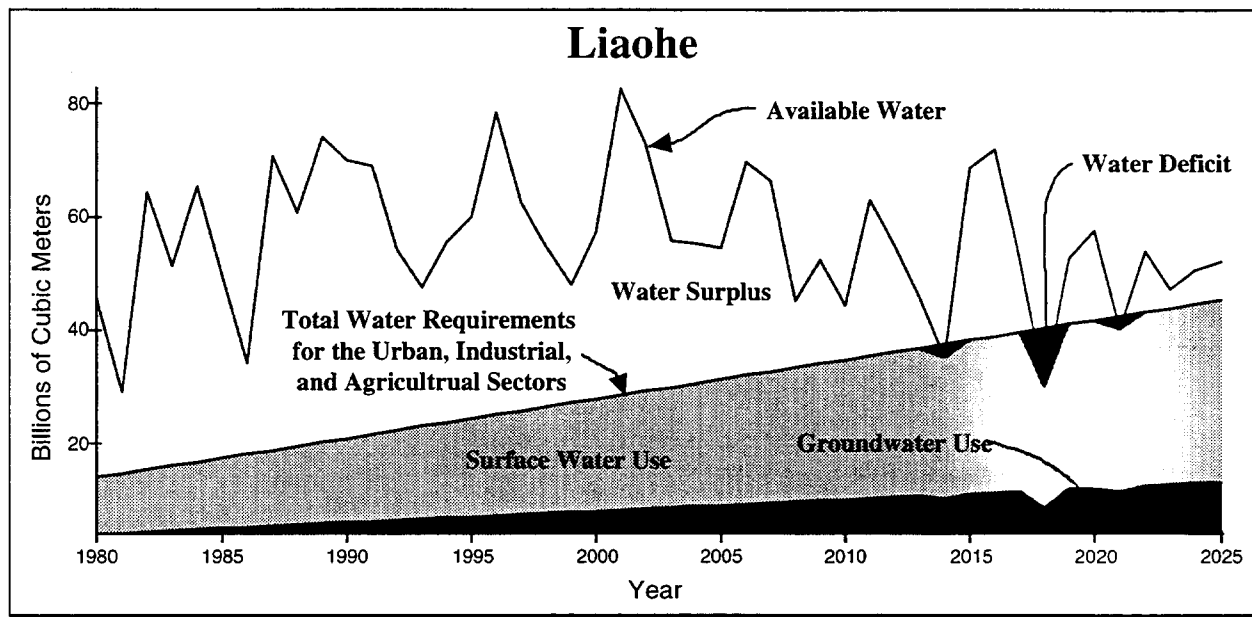


Figure C-4. Comparison of the results of a single run of stochastic modeling of available water with linear projection of total water requirements in the Liaohe Basin.

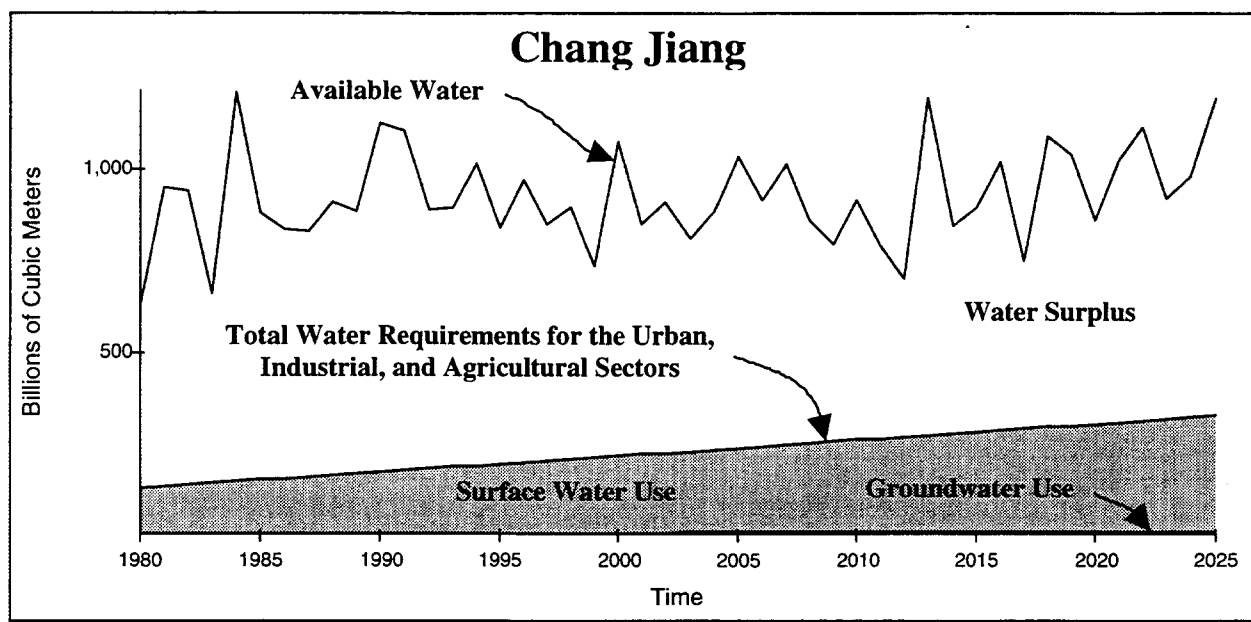


Figure C-5. Comparison of the results of a single run of stochastic modeling of available water with linear projection of total water requirements in the Chang Jiang Basin.

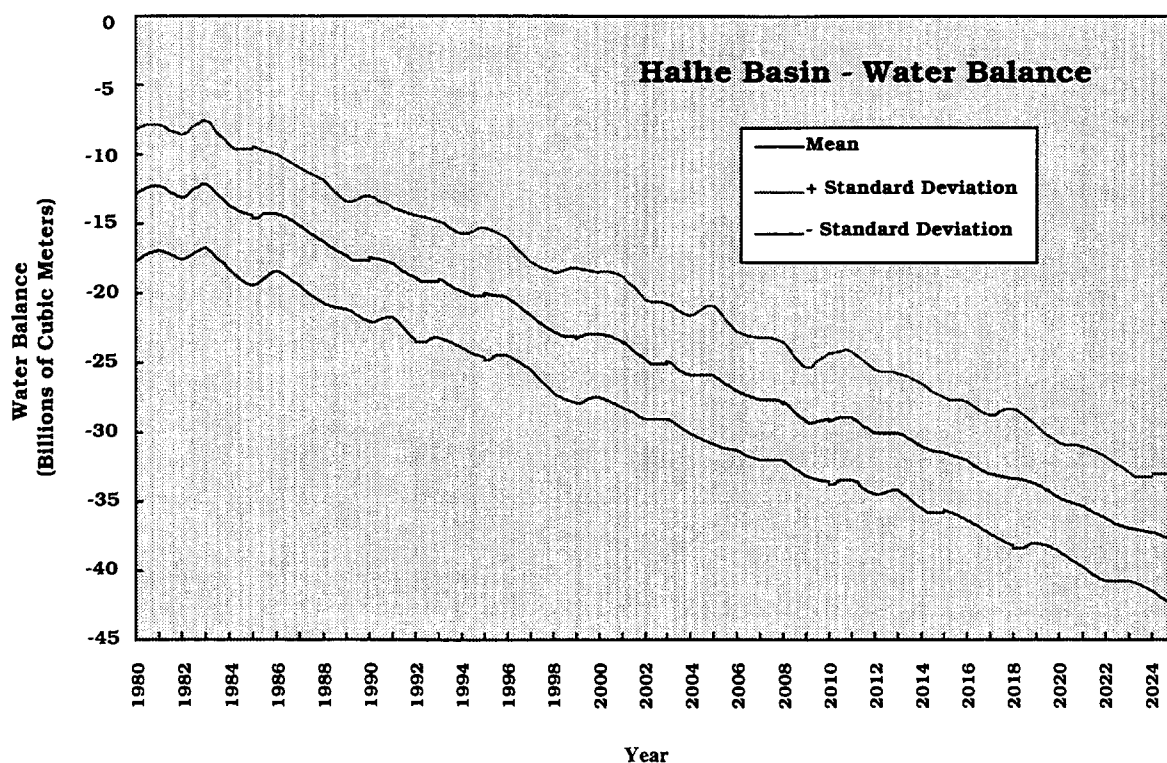


Figure C-6. Predicted water deficit for the Haihe Basin through the year 2025 generated in 100 runs of the simulation model.

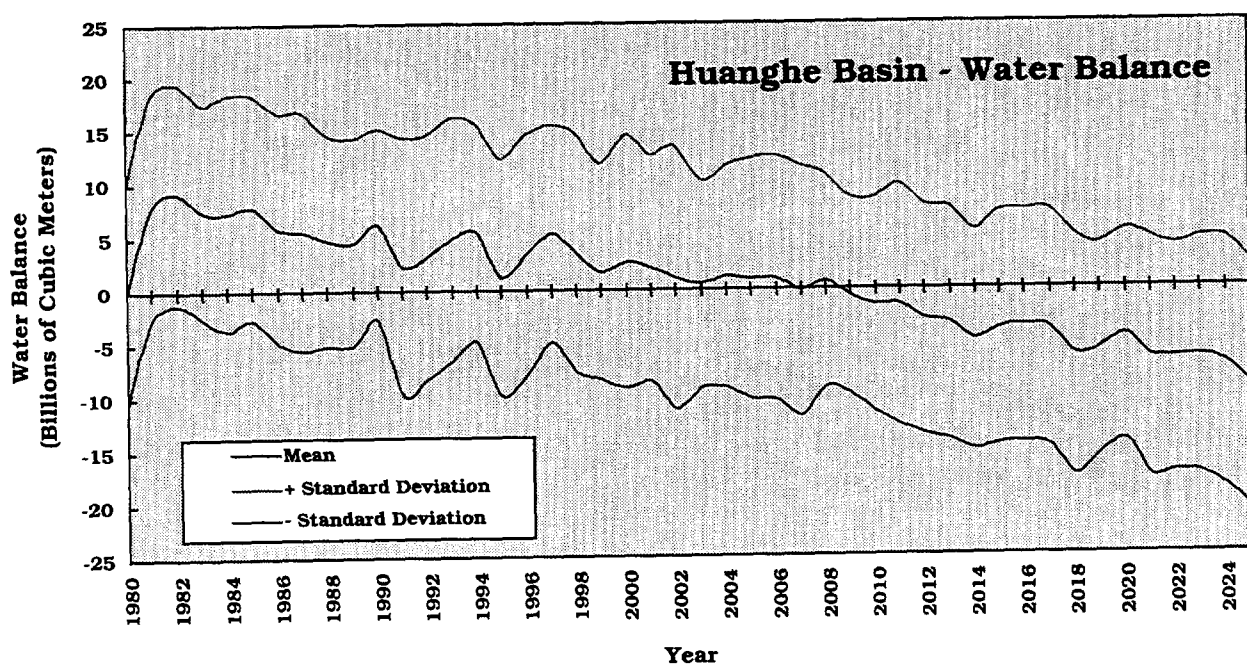


Figure C-7. Predicted water deficit for the Huanghe basin through the year 2025 generated in 100 runs of the simulation model.

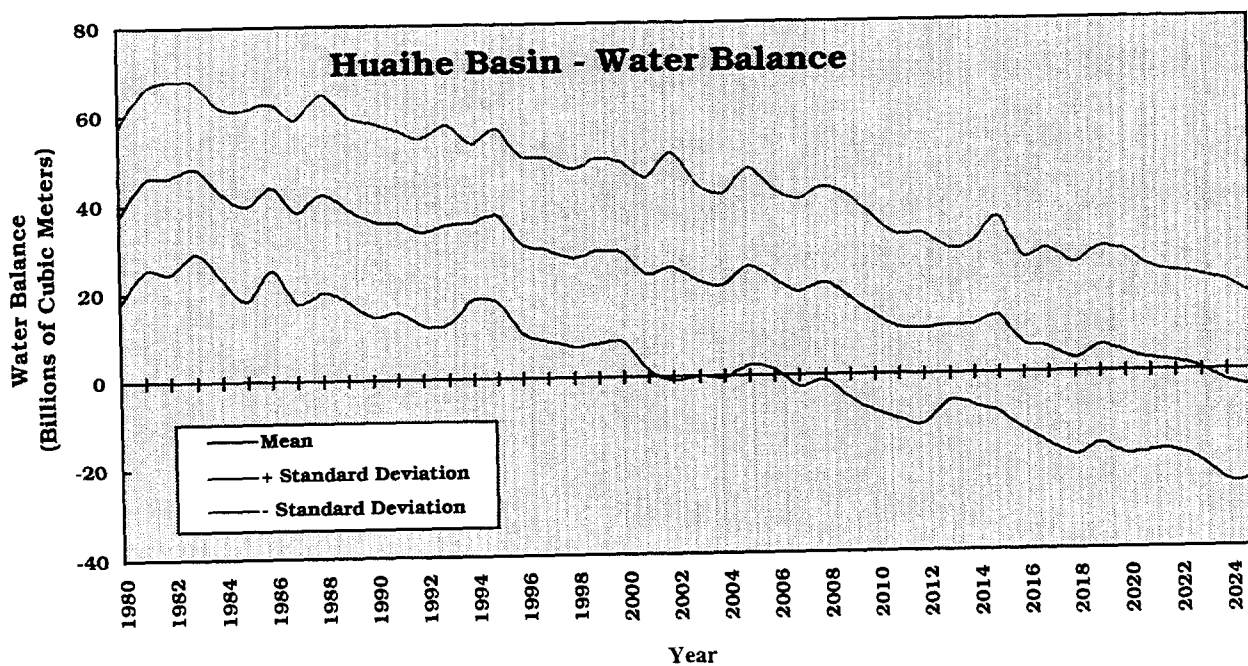


Figure C-8. Predicted water deficit for the Huaihe basin through the year 2025 generated in 100 runs of the simulation model.

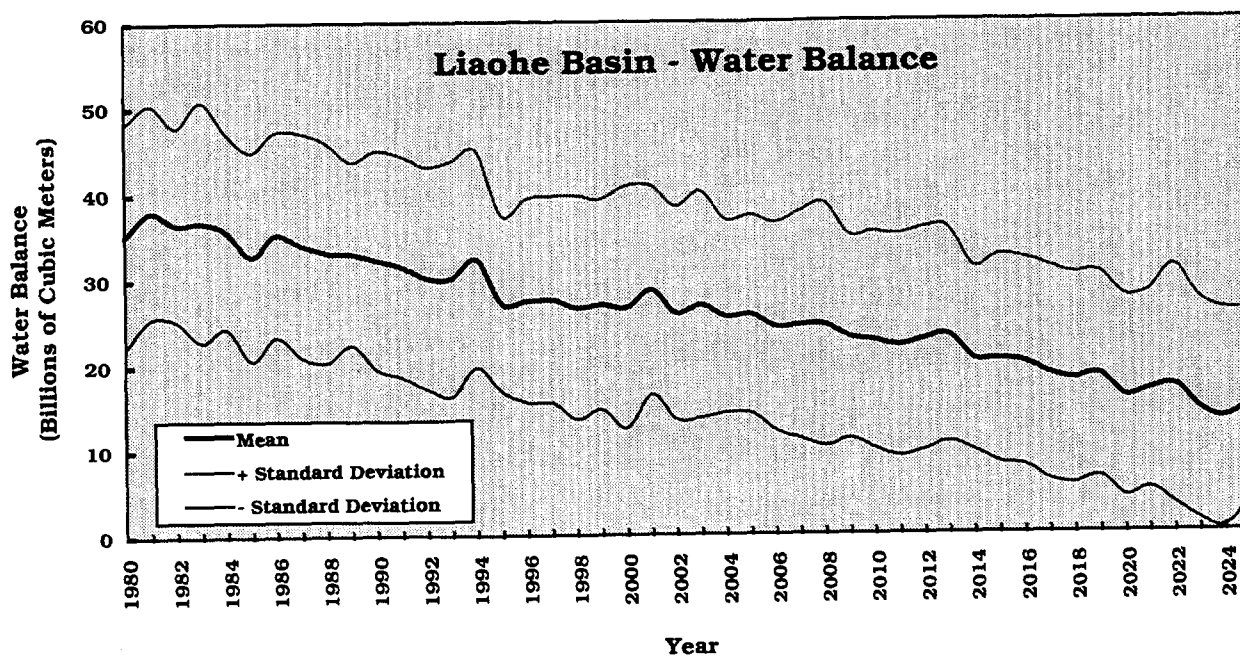


Figure C-9. Predicted water surplus for the Liaohe basin through the year 2025 generated in 100 runs of the simulation model.

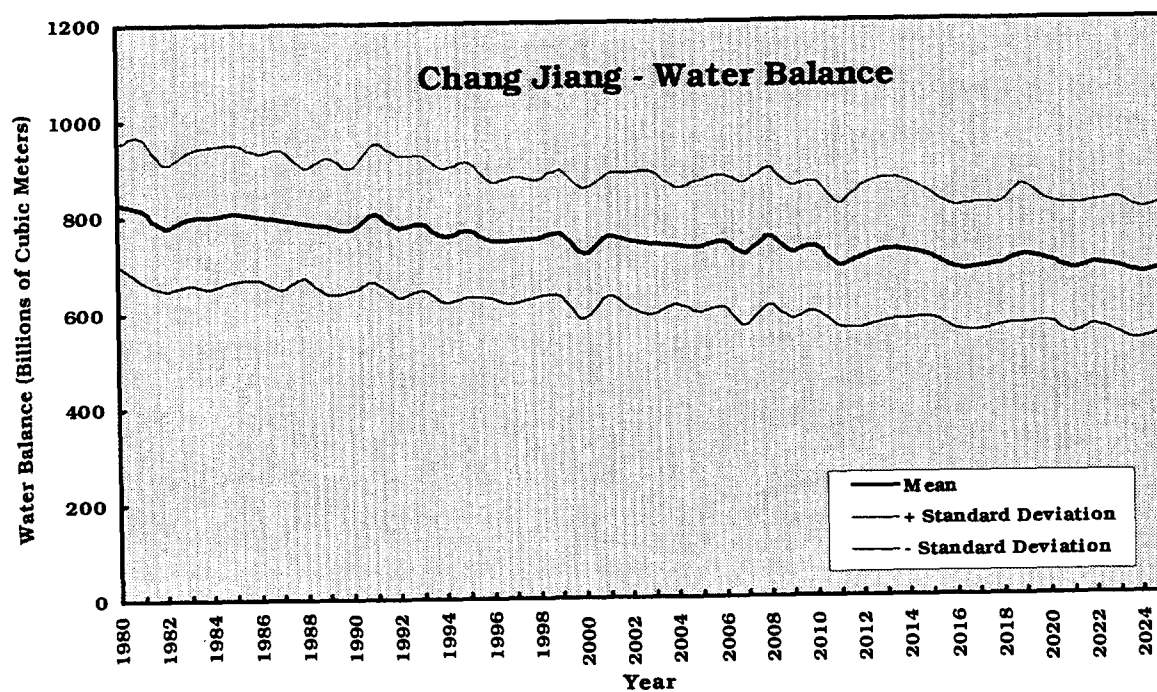


Figure C-10. Predicted water surplus for the Chang Jiang basin through the year 2025 generated in 100 runs of the simulation model.

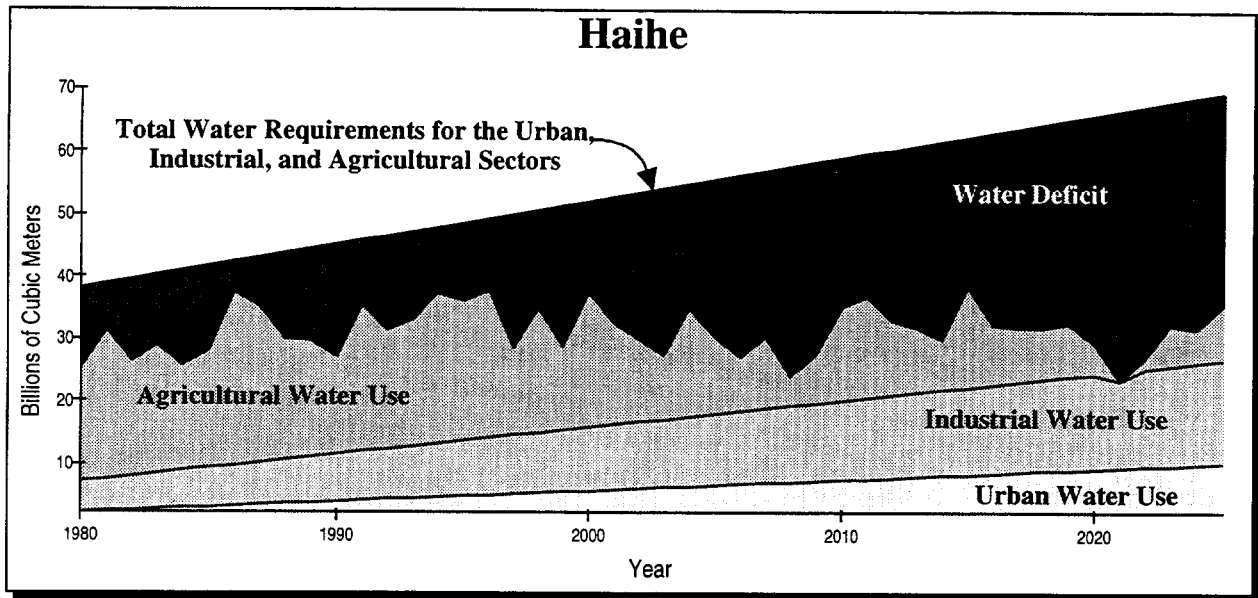


Figure C-11. Comparison of the results of a single run of stochastic modeling of total available water and water use in the urban, industrial, and agricultural sectors with linear projection of total water requirements in the Haihe Basin.

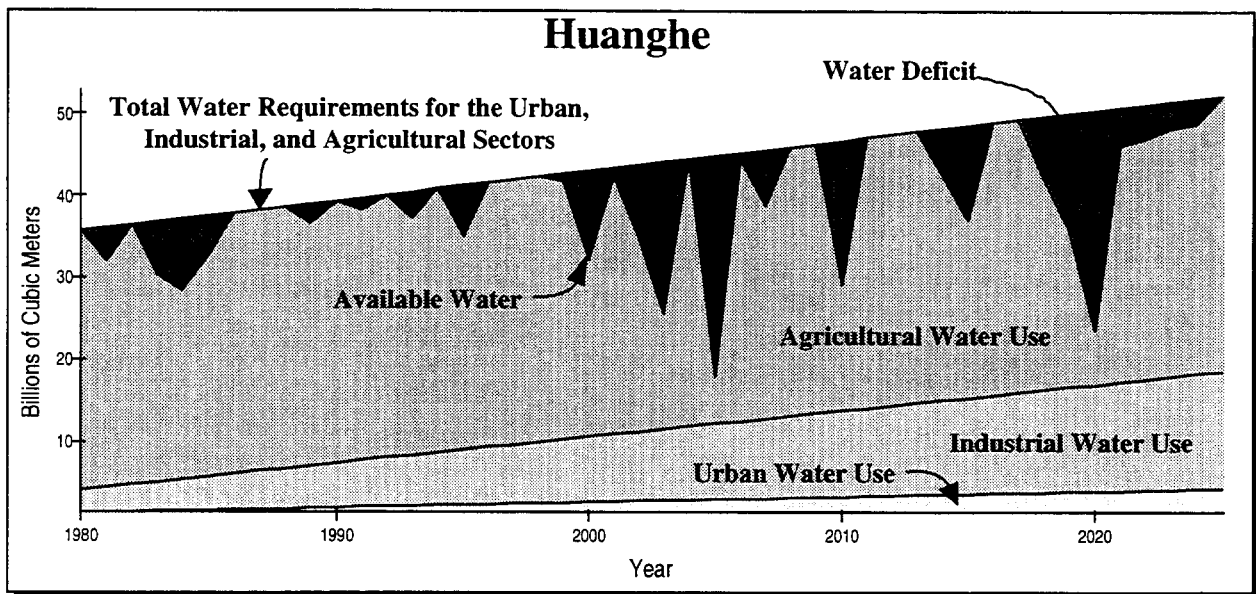


Figure C-12. Comparison of the results of a single run of stochastic modeling of total available water and water use in the urban, industrial, and agricultural sectors with linear projection of total water requirements in the Huanghe Basin.

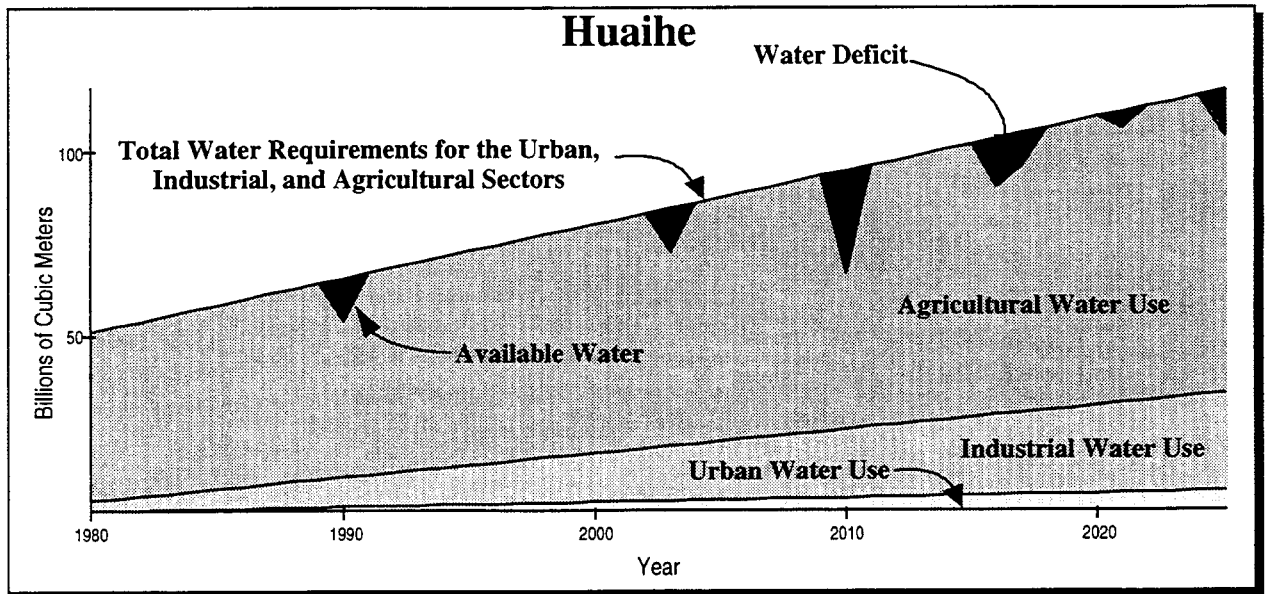


Figure C-13. Comparison of the results of a single run of stochastic modeling of total available water and water use in the urban, industrial, and agricultural sectors with linear projection of total water requirements in the Huaihe Basin.

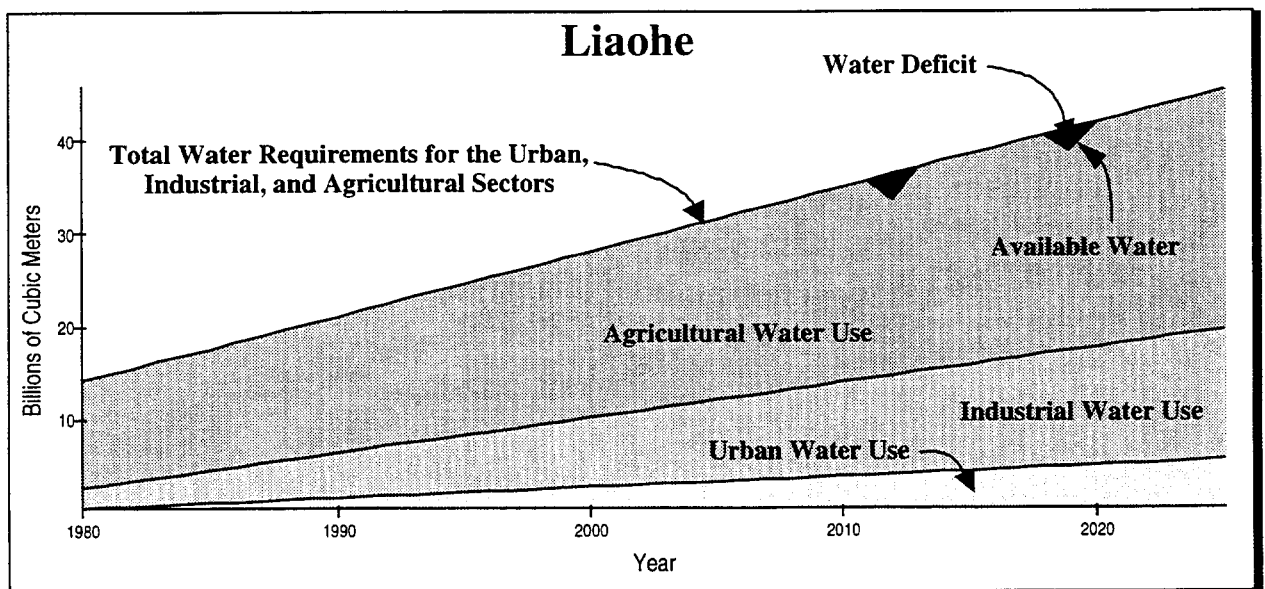


Figure C-14. Comparison of the results of a single run of stochastic modeling of total available water and water use in the urban, industrial, and agricultural sectors with linear projection of total water requirements in the Liaohe Basin.

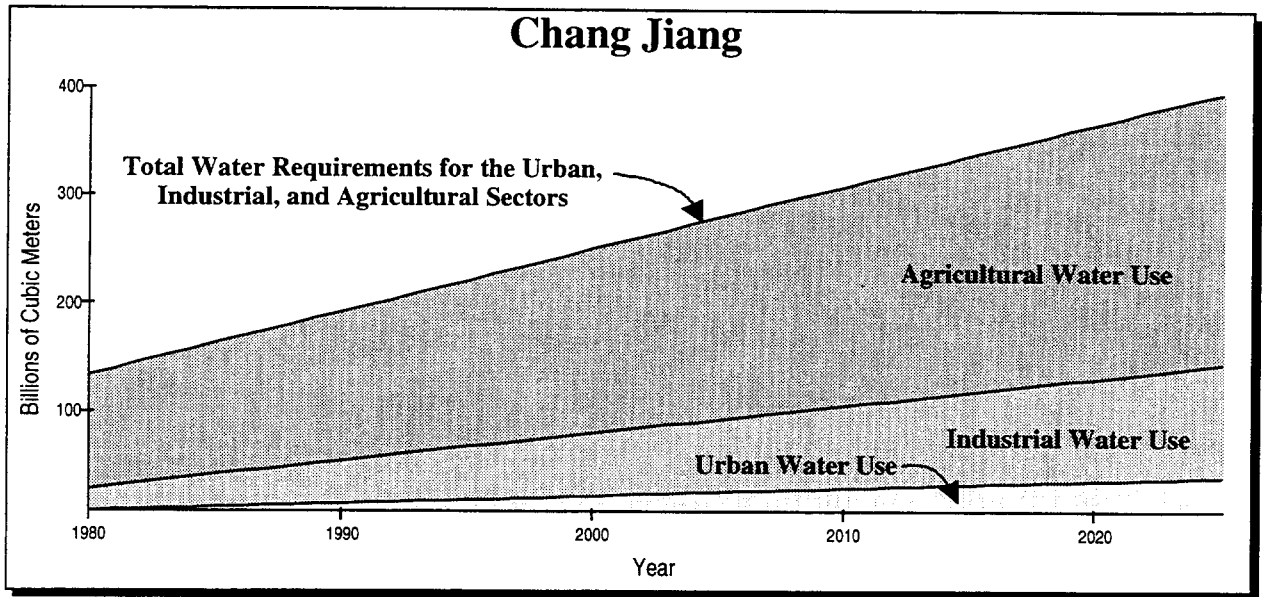


Figure C-15. Comparison of the results of a single run of stochastic modeling of total available water and water use in the urban, industrial, and agricultural sectors with linear projection of total water requirements in the Chang Jiang Basin.

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